Opportunities in x-ray metrology with synchrotron radiation

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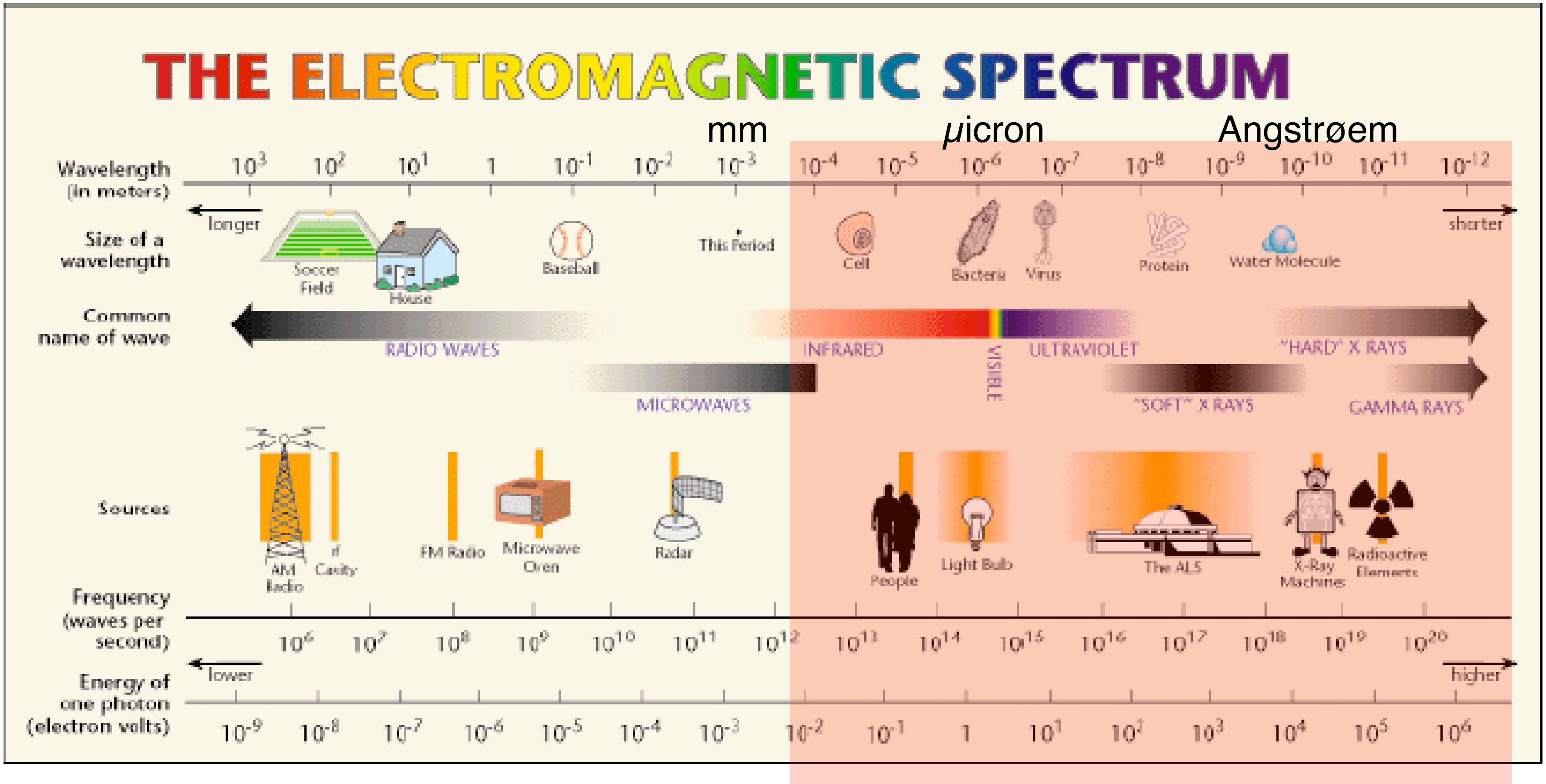
METROLOGY:
Measurement Science and Technology

Given that metrology is the science of measurement, inevitably, it is also the science of **precise & accurate** measurement.

Furthermore, since measurements by definition should be as less invasive as possible, electromagnetic radiation from radio waves, to microwaves, to infrared, to visible, x-ray and gamma rays are all part of metrology.

Many major “National Standards” institutes had and continue to have active metrology groups, and some of them have x-ray metrology.

However, there is still no length or weight standard, for example, that connects astronomical units to atomic units or smaller. In other words, for every standard, there is a “limited” dynamic range. It remains a continuos challenge to extend this range, and connect different approaches.



Synchrotron radiation

In the beginning .....

Four quantities: **length, area, volume, and weight**, which were NOT not distinguished from each other.

Ancient people used **time** to measure large **lengths** and **areas**. For example, a journey was so many hours, days, or moons rather than measured miles. Many ancient measures were derived from body parts or easily obtainable materials. We still use foot and the hands when measuring length.

The inch was based on the length of the last joint of the thumb, yard was the distance from the tip of the nose to the end of the fingers with the right arm outstretched.

Early attempts to to define the lengths in terms of some standard was to use the distance from the King's nose to the fingers of his outstretched arm, for example. The earliest preserved standard for length is the foot of a statue of Gudea, the governor of Lagash, a Mesopotamian city of about 4000 years ago.

Over the centuries, mostly due to commercial concerns, measurements became more demanding. Thus, agreeable standards and measurement itself became more precise. In fact, measurement became so precise that it required a new name to distinguish it from the casual and imprecise...

... that name is METROLOGY.

Gudea of Lagash

2141-2122 B.C.
Mesopotamian,
Neo-Sumerian period

International Bureau of Weights and Measures (BIPM)

Metrology : "the science of measurement, embracing both experiment and theoretical determinations at any level of uncertainty in any field of Science and Technology."

Historical origins date back to early humans, but the modern usages is usually attributed to **French Revolution.** The was a political motivation to **harmonize units** all over France and the concept of establishing units of measurement based on constants of nature, and thus making measurement units available ***"for all people, for all time"***.

The result was two platinum standards for the meter and the kilogram established as the basis of the metric system on June 22, 1799. This further led to the creation of the **Système International d'Unités (SI) ,** or the International System of Units

Today, METROLOGY is a very broad field and may be classified as follows:

* **Scientific or fundamental metrology:**

Establishment of measurement units, unit systems, the **development** of new measurement methods, **realization** of measurement standards and the **transfer** of **traceability** from these standards to users in society.

* **Applied or industrial metrology:**

Application of measurement science to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration and quality control of measurements.

* **Legal metrology**

Regulatory requirements of measurements and measuring instruments for the protection of health, public safety, the environment, enabling taxation, protection of consumers and fair trade.

International Metrology Institutes

ARL, Australian Radiation Laboratory, Australia
BIPM, Bureau International des Poids et Mesures, France
BNM-LCIE, Laboratoire Central des Industries Electriques, France
BNM-LNE, Laboratoire National D' Essais, France
CENAM, Centro Nacional de Metrología, Mexico
CMI, Czech Metrological Institute, Czech Republic
CMS, Taiwan
CNAM, Conservatoire National des Arts et Métiers, France
CSA, Canadian Standards Association, Canada
CSIRO, The Commonwealth Scientific and Industrial Research Organisation, Australia
DFM, Danish Institute of Fundamental Metrology, Denmark
EIN, Hellenic Institute of Metrology, Greece
ENEA, Istituto Nazionale di Metrologia delle Radiaziono Ionizzanti Roma, Italy
ETL, Electrotechnical Laboratory, Japan
HUT Metrology Research Institute (MRI), Finland
EN, Istituto Elettrotecnico Nazionale Galileo Ferraris, Italy
IEP, Instituto Electrotécnico Português, Portugal
MGC, Istituto di Metrologia "G. Colonnetti", Italy
INEN, Instituto Ecuatoriano de Normalizacion, Ecuador
NMETRO, Instituto Nacional de Metrologia, Normalização e Qualidade Industrial, Brazil
NN, Instituo Nacional de Normalización, Chile
INTI, Instituto Nacional de Tecnología Industrial, Argentina
INTN, Instituto Nacional de Tecnología y Normalización, Paraguay
PQ, Portugal

Justervesenet (National Measurement Service), Norway
KRISS, Korea Research Institute of Standards and Science
LATU, Uruguay
MIKES, Mittatekniikan Keskus, Finland
NIMC, National Institute of Material and Chemical Research, Japan
NIST, National Institute of Standards and Technology, USA
NML, National Metrology Laboratory, Ireland
NML, National Metrology Laboratory, South Africa
NMI, Nederlands Meetinstituut, Netherlands
NPL, National Physics Laboratory, India
NPL, National Physical Laboratory, UK
NRC, National Research Council Canada
NRLM, National Research Laboratory of Metrology, Japan
NRPA, Sweden
OFMET, Swetzerland
OMH, Országos Mérésügyi Hivatal, Hungary
PTB, Physikalisch-Technische Bundesanstalt, Germany
BAM, Bundesanstalt für Materialforschung und -prüfung
SABS, South African Bureau of Standards, South Africa
SASO, Saudi Arabian Standards Organization, Saudi Arabia
SFS, Finland
SIRIM, Standards and Industrial Research Institute of Malaysia
SMIS, Standards and Metrology Institute of Slovenia
SP, Sweden
SPRING, Singapore
VNIIM, Russia

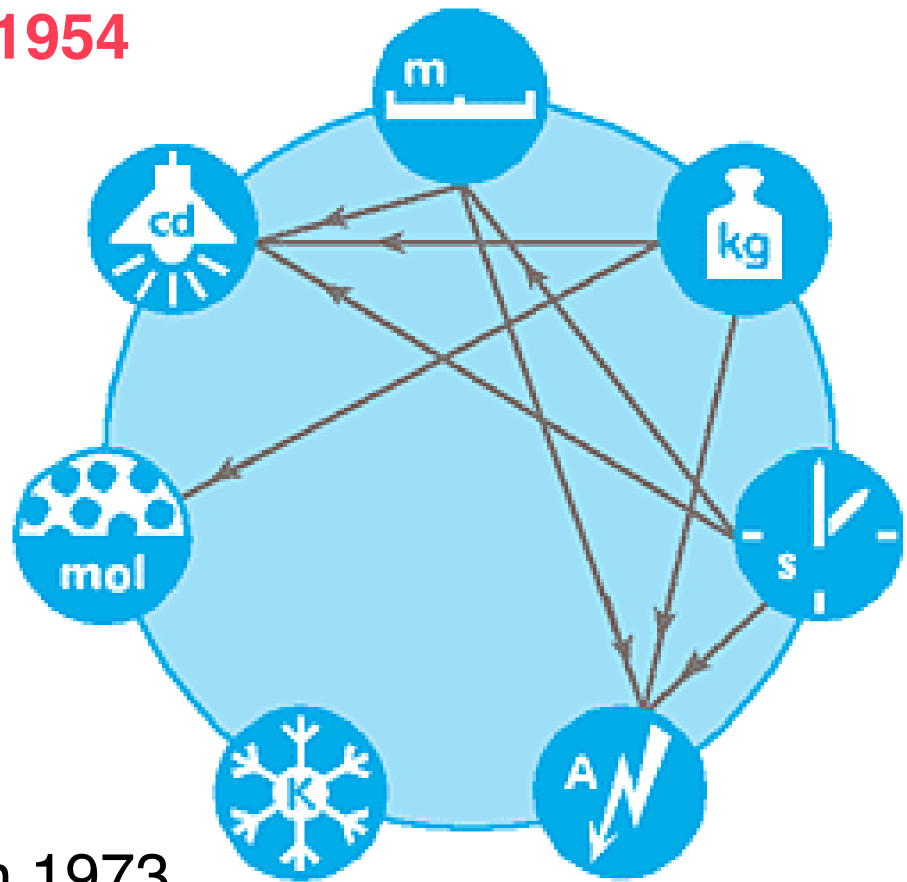
General Conference on Weights and Measures, 1954

<u>The six base units:</u>

length (meter),
mass (kilogram),
time (second),
electric current (ampere),
thermodynamic (kelvin) and
luminous intensity (candela).

<u>and the seventh was added in 1973</u>

the amount of substance (mole)

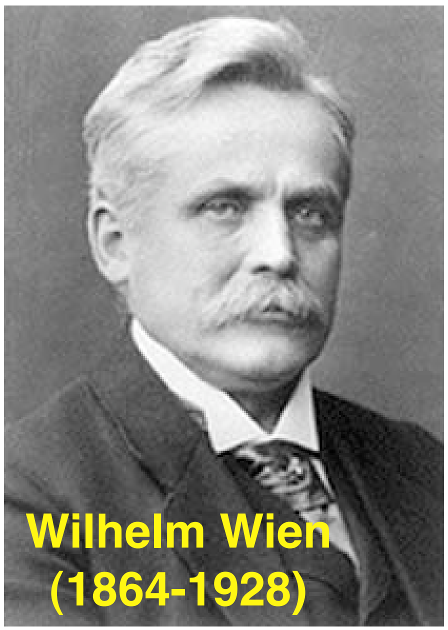


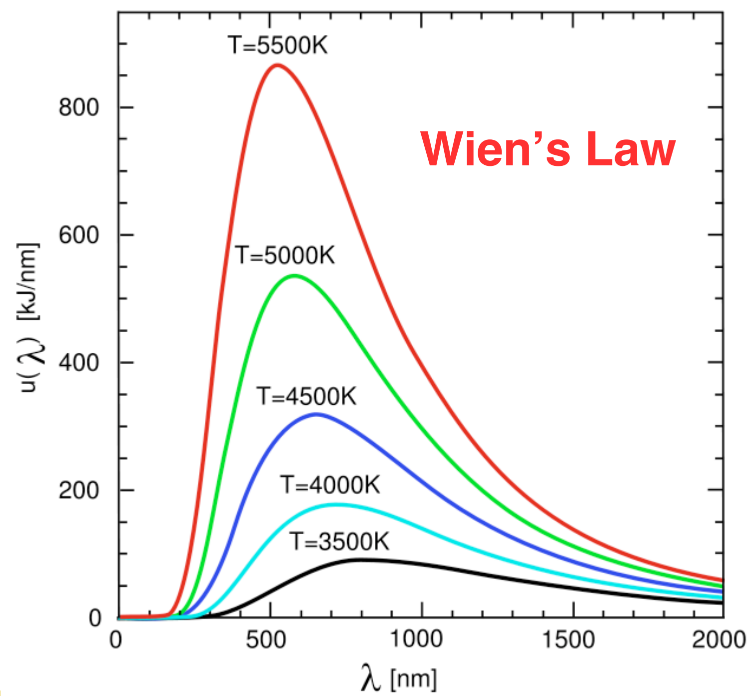
Birth of Quantum Mechanics

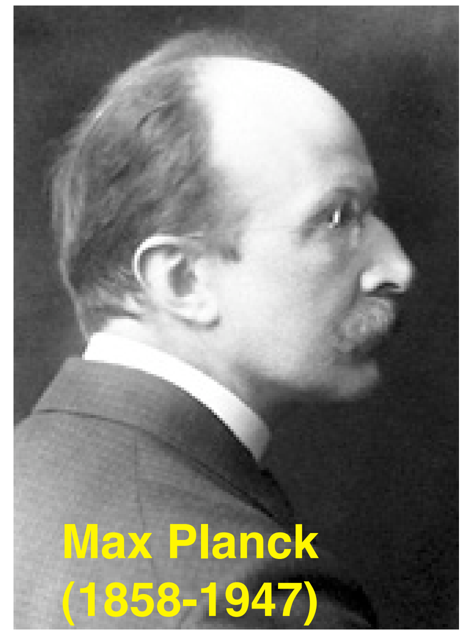
Planck was able to deduce the relationship between the energy and the frequency of radiation (1900)

Wien developed a formula for determining the energy density associated with particular wavelengths for any given temperature of a radiating body(1901).

Their contributions to the field of radiation laid the foundation for the development of the quantum theory



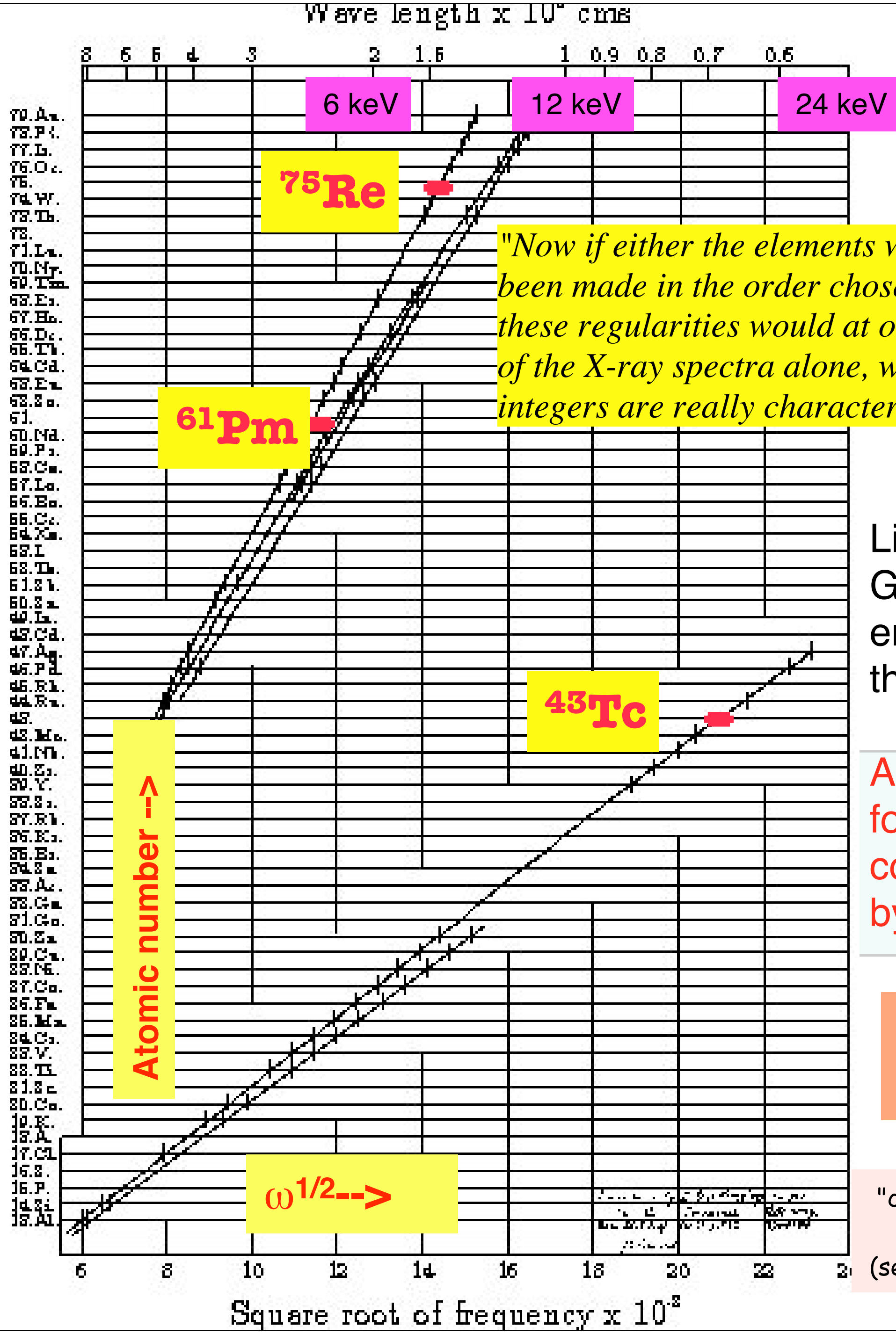




$$\lambda_{\max} = \frac{b}{T}, \quad \mathrm{b} = 2.897768\,5(51) \cdot 10^{6}\ \mathrm{nm} \cdot \mathrm{K}$$

$$\mathrm{u}(\lambda, \mathrm{T}) = \frac{8\pi hc}{\lambda^{5}} \frac{1}{e^{hc/\lambda kT} - 1}$$

H.G. J. Moseley (1914)



"Now if either the elements were not characterized by these integers, or any mistake had been made in the order chosen or in the number of places left for unknown elements, these regularities would at once disappear. We can therefore conclude from the evidence of the X-ray spectra alone, without using any theory of atomic structure, that these integers are really characteristic of the elements."

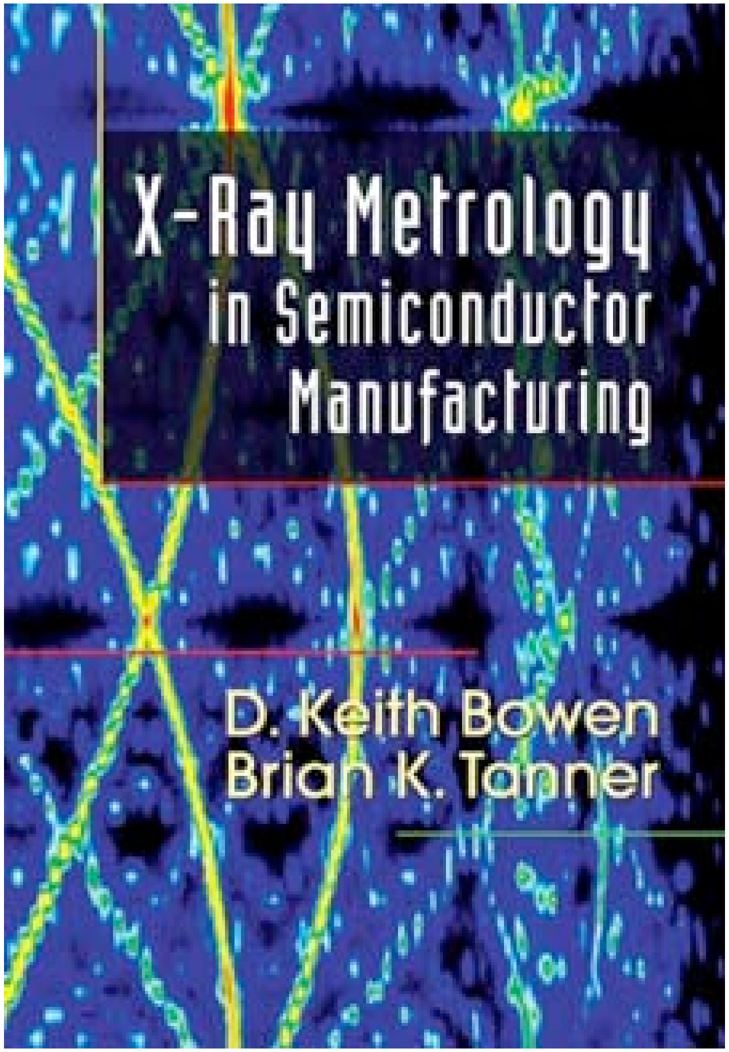
Like Mendeelev's prediction of presence of Ga and Ge, Moseley, by plotting x-ray spectral energies against an integer number, predicted the presence of Tc, Pm,Hf, Os, and Re.

Another mystery was the presence of 2 lines for K-edges, and 4 lines for L-edges. This mystery could only be solved after the discovery of spin by Dirac.

Such a linear relationship does not exist
In nuclear transitions

"curve drawn by H. G. J. Moseley in 1914 in the Electrical Laboratory.

(see Phil. Mag. Vol. 27. P703 April 1914) J S Townsend)."



2006

* Specular X-Ray Reflectivity (XRR)
* Diffuse Scattering
* High-Resolution X-Ray Diffraction
* Diffraction Imaging and Defect Mapping
* X-Ray Fluorescence
* Thickness Metrology
* Multiple Layers, Epitaxial Layers
* Composition and Phase Metrology
* Amorphous & Polycrystalline Films
* Wafers and Epitaxial Films
* Strain and Stress Metrology
* Relaxation of Epitaxial Layers
* Thin Strained Silicon Layers
* Whole Wafer Defect Metrology
* Mosaic Metrology
* Grain Size Measurement
* Mosaic Structure in Substrate Wafers & Epilayers
* Interface Width and Roughness Metrology
* Porosity Metrology
* Determination of Pore Size and Distribution
* Pores in Single Crystals

state-of-the-art advances in science, technology, require and demand instrument development.

Some of the current driving forces for new metrology solutions for industry:

- the increasing volume and complexity of compound semiconductor epitaxial wafers,

- more challenging tolerances on band-gap engineering,

- the challenge of measuring compound semiconductor device parameters at wafer level (maximize fab yields)

- the introduction of novel nanostructured materials (high-k dielectrics, ferroelectrics, polymers) in CMOS microelectronics, optoelectronics and in a variety of microsystems.

Current Standards

Length standard (1983 - present) :

The meter has been defined as the distance traveled by light in 1/299 792 458 of a second. Speed of light becomes constant, and length standard is defined ($\lambda_s = c/f_s$) by the frequency of ^{133}Cs clock.

Length standard at interatomic distances (1994)

633 nm He-Ne laser is too long for atomic distances. The LLL interferometer of Hart is combined with a Fabry-Perot light interferometer to provide the link. Today, Si lattice constant, a_0= 5.43020188(16) Å at 22.5°C and 1 atm, is used as a length standard for interatomic distances.

Deslattes, R. D. and Henins, A.: 1973, X-ray to visible wavelength ratios, *Phys. Rev. Lett.* **31**, 972.
Bonse, U. and Hart, M.: 1965b, An x-ray interferometer, *Appl. Phys. Lett.* **6**, 155.

Mass : (1899 - present)

The iridium-platinum alloy (from a single charge) at BIPM in Sevre, France is the current standard of mass. This is the only SI unit defined in terms of an artifact. It ages, and loses ~50 μg/100 year.

Avogadro Project

COXI: Combined Optical and X-Ray Interferometry

IMGC, NRML, PTB, NIST, IMMR, CSIRO-NML, IMR

- Instituto de Metrologia "G. Colonetti", ITALY
- National Research Laboratory of Metrology, JAPAN
- Physikalisch-Technische Bundesanstalt, GERMANY
- National Institute of Standards and Technology, USA
- Institute for Reference Materials and Measurements, EU, Geel
- Commonwealth Scientific and Industrial Research Organization
    - National Measurement Laboratory, AUSTRALIA
- Institute of Mineral Resources, CHINA

$$N_A = 6.0221339(27) \times 10^{23}/\text{mol}$$

Avogadro's constant

Current definition of mass at macroscopic scale is about 113 years old, made of Pt-Ir at Bureau International des Poids et Measures (BIPM) in Sévres, France.

The project attempts to definethe mass at atomic scale through perfect crystal of silicon:

$$N_A = \frac{Si - molar\ volume}{Si - atomic\ volume} = nM_{Si}v / V_0 m$$

n= no. of Si atoms/unit cell, M=mass of Si, ν=volume, V_0=**unit cell volume**, m=mass

$$N_A = 6.0221339(27) \times 10^{23}$$

Silicon lattice constant

Currently, the Si lattice constant

a_0= 5.43020188(16) Å at 22.5°C and 1 atm

relative uncertainty = 2.94×10^{-8}

is used as a way to transfer x-ray wavelengths to visible wavelength scale by combining x-ray interferometry with optical interferometry. (Deslattes, Hart,Becker)

G. Basile, et al, Proc. R. Soc. London A 456 (2000) 701

Uncertainties in Si as a wavelength standard

There are reproducibility problems due to presence of :

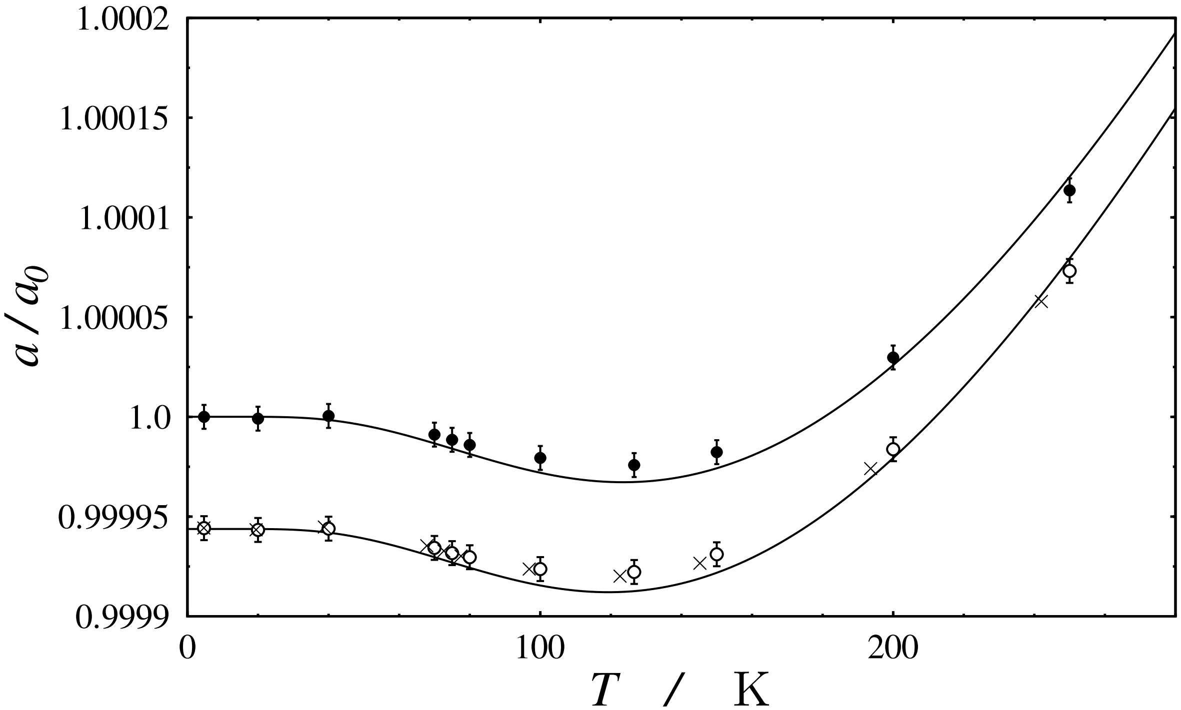
- impurities, (N=10 ppb, C=60 ppb, O=40 ppb, S,V= 20 ppb)
- vacancies, self-interstitials
- isotopic purity (^{28}Si=92.23%, ^{29}Si=4.67%, ^{30}Si=3.1%)
- surface defects (etch pits, voids, cracks)
- surface oxide formation
- temperature,
- stress

There are problems associated with CVD deposited isotopically pure Si (mass separation due to thermo-diffusion), as well as FZ or Chochralski grown crystals (oxygen defects, voids)

Anomalous Isotopic Effect on the Lattice Parameter of Silicon

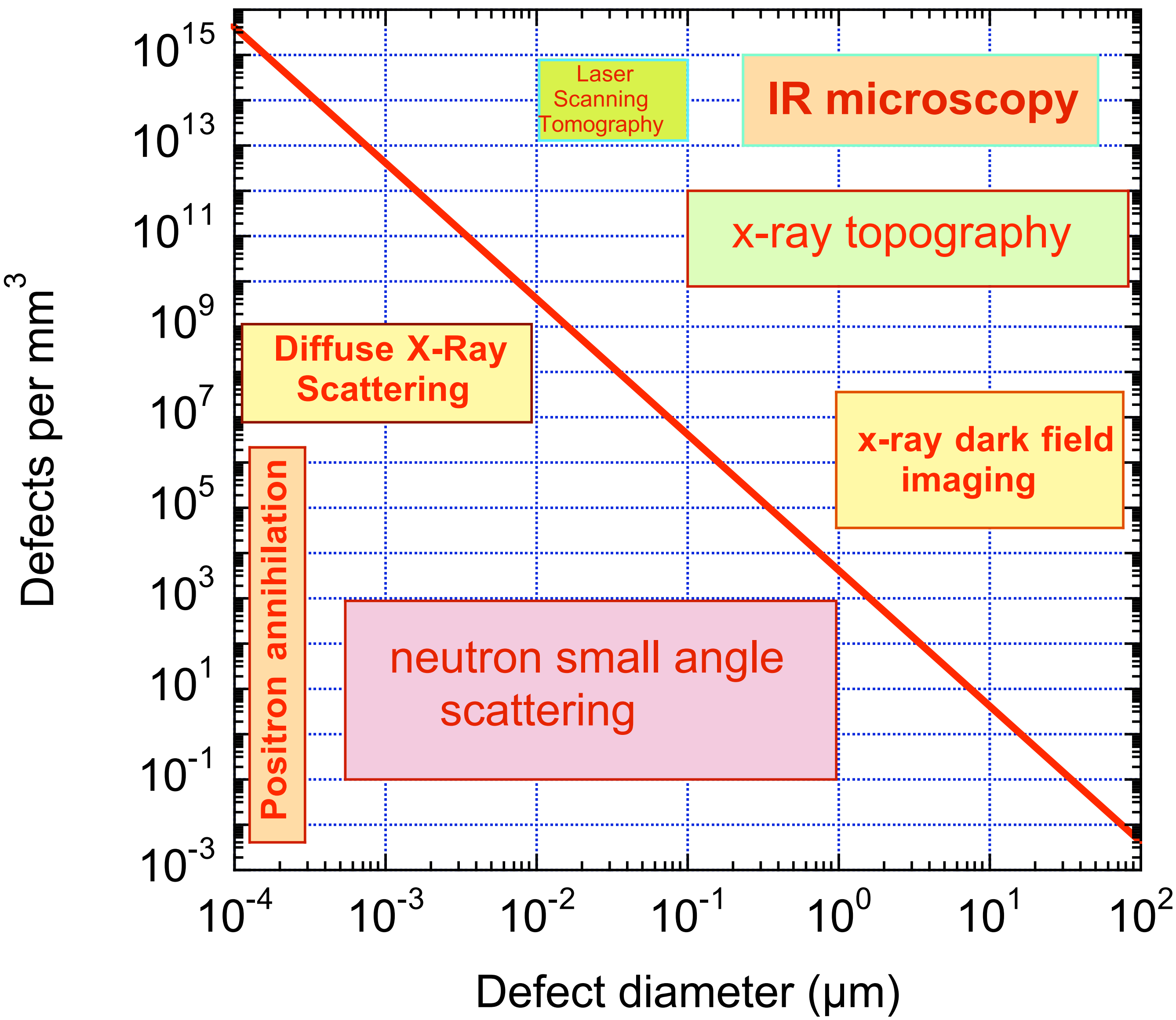
H.-C. Wille, Yu. V. Shvyd'ko,* E. Gerdau, M. Lerche, M. Lucht, and H. D. Rüter
Institut für Experimentalphysik, Universität Hamburg, D-22761 Hamburg, Germany

J. Zegenhagen
European Synchrotron Radiation Facility, F-38043 Grenoble Cedex, France



Approaches for defect density determination

(after P. Becker, IEEE Trans. Instr. Measur. 50 (2001) 612)



The measurement of the electrical resistivity of silicon*

By R. H. CREAMER, M.Sc., A.Inst.P., The General Electric Co., Ltd., Wembley, Middlesex

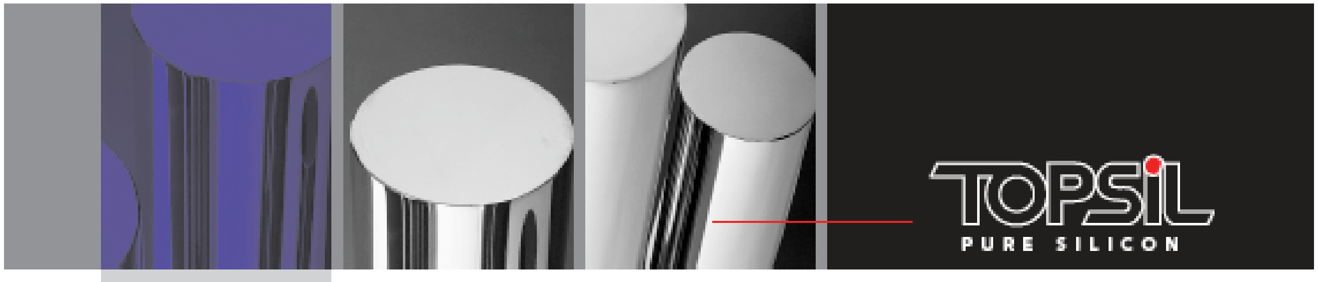
[*Paper received* 19 *December*, 1955]

Resistivity measurements by the normal and the four-probe methods

	Normal method		Four-probe method		
Specimen reference	*Measured resistivity (Ω cm)*	*Standard error*	*Probe treatment*	*Measured resistivity (Ω cm)*	*Standard error*
1	2·88	0·02	nil	2·86	0·09
(*n*-type)			electroformed	2·84	0·03
2	8·00	0·08	nil	7·80	0·56
(*p*-type)			electroformed	8·00	0·11
3	26·80	0·16	nil	†	†
(*n*-type)			electroformed	26·00	0·37
4	150·0	3·5	nil	†	†
(*n*-type)			electroformed	157	4
5(*a*)*	229	8	nil	†	†
(*n*-type)			electroformed	222	25
5(*b*)*	1627	87	nil	†	†
(*n*-type)			electroformed	1650	225

* Non-uniform resistivity along specimens.

† Fluctuating current in specimen.



Growth method	Neutron Transmutation Doped Float Zone Silicon
Bulk resistivity range	5-4000 Ωcm
Resistivity tolerance	±5% - ±10%*
Radial resistivity variation (ASTM F81 planC)	< 3% - < 8%*
Striations	Not detectable
Minority carrier lifetime	> 300 μs depending on bulk resistivity
Ingot diameter	50-154 mm
Crystal orientation	<100>, <111>**
Type and Dopant	N (phosphorous)
Oxygen and Carbon concentration	$< 10^{14}$ cm^{-3}
Wafer thickness	> 200 μm depending on wafer diameter
Wafer surface finish	As-cut, Lapped, Etched, Grinded, Polished

*Depending on bulk resistivity and ingot diameter.
**<111> is not available in 6" diameter.

Neutron Transmutation Doped Silicon for Power Applications

Neutron Transmutation Doped (NTD) monocrystalline silicon is grown by irradiating undoped Float Zone silicon with neutrons. During irradiation and subsequent annealing of the ingots silicon atoms Si30 is converted into P31 which is a n-type doping. By controlling the dose and the width of the irradiating neutron beam the resistivity variation can be kept at record low values over a large range of bulk resistivities ranging from 10 Ohm-cm to 4000 Ohm-cm. No other method of producing monocrystalline silicon can produce these low resistivity variations over the whole of the crystal.

(http://www.topsil.com/397)

Highest theoretical resistivity for pure Si is 250 k-ohm-cm.

In reality, the highest resistivity available is ~ 100 k-ohm-cm.

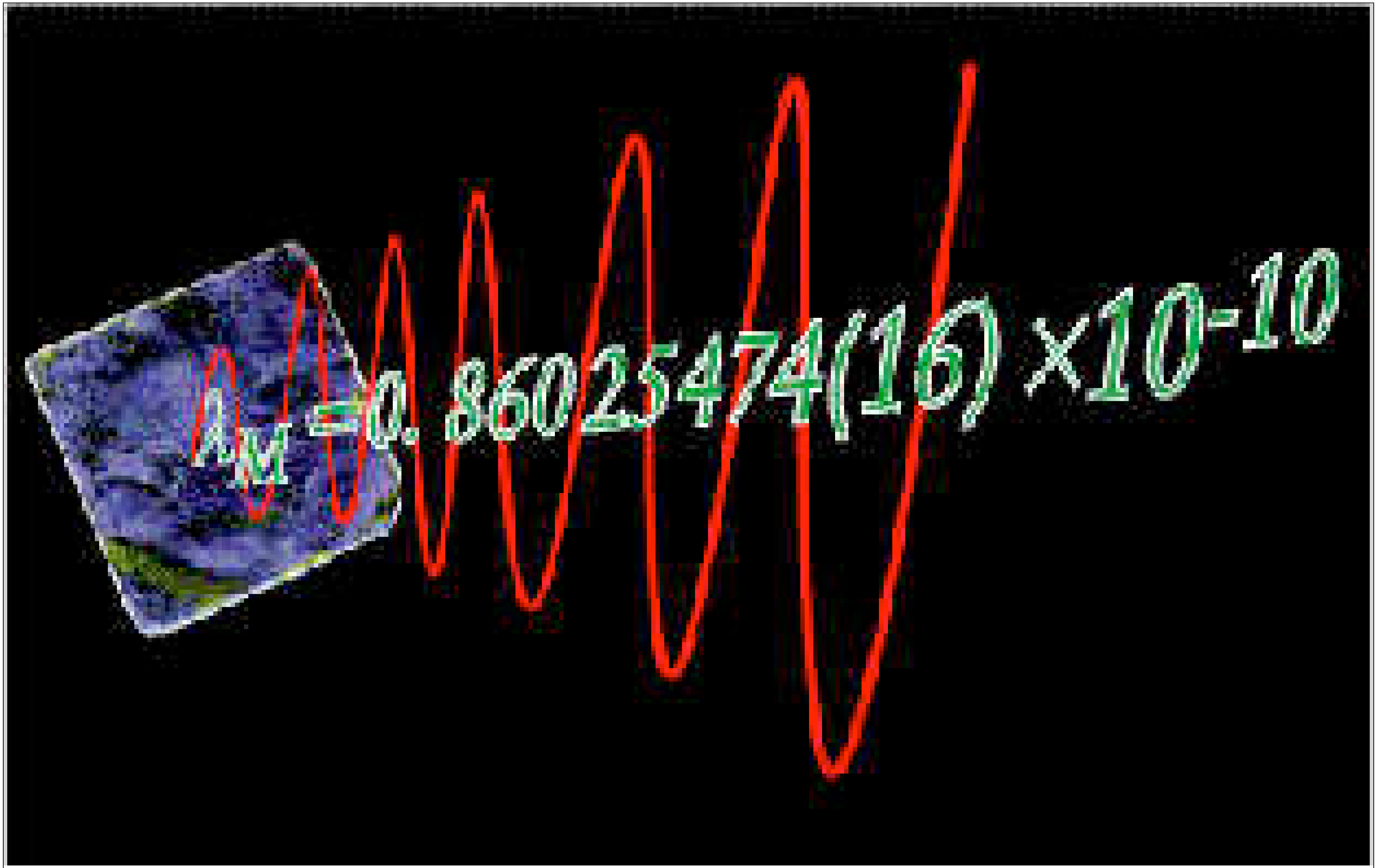
The difficulty is to ensure uniformity of this value over a large length and area.

Measuring wavelengths and lattice constants with Mössbauer wavelength standard

- Higher accuracy ($\Delta E/E \sim 10^{-13}$ possible)
- Reproducible: independent of temperature, pressure, composition, and other parameters
- Available between 6-100 keV range at more than a dozen energies

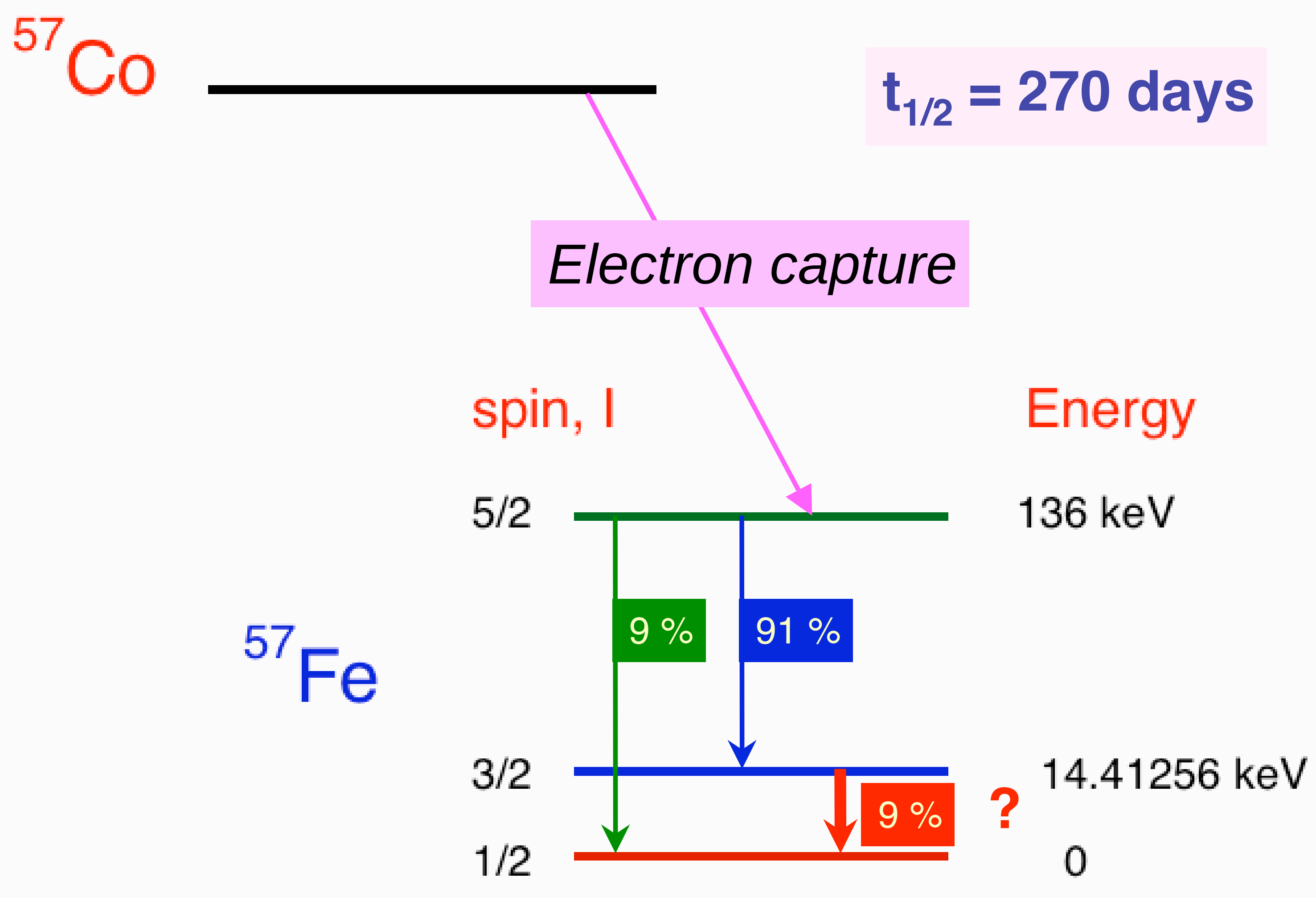
J. Synchrotron Rad. 9 (2002) 17-23.

Phys. Rev. Lett. 85 (2000) 495.



Phys.Rev.Lett., 45 (2000) 495

Characteristics of nuclear excitation and decay



λ-meter

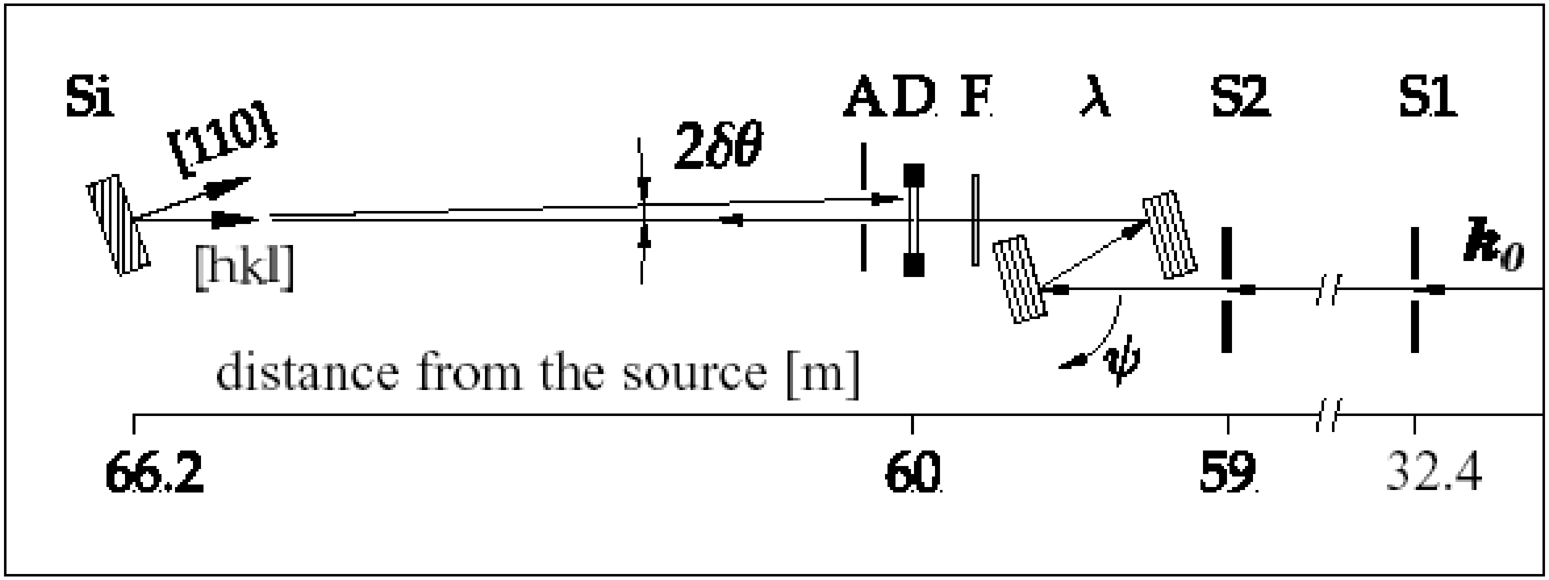
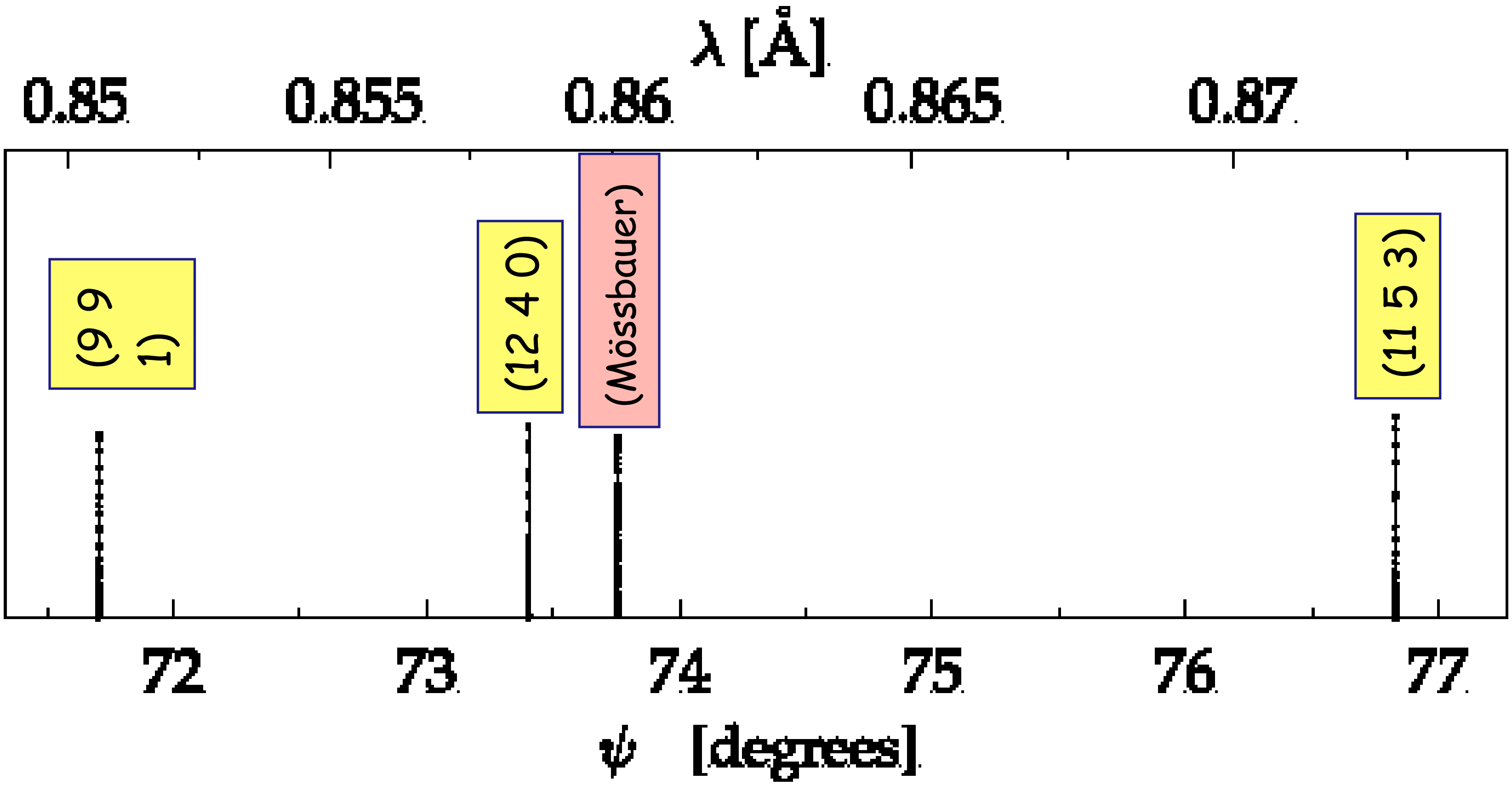


Figure 4.1: Schematic of the experiment: the radiation after a high-heat-load premonochromator (not shown) passes through the vertical slits S1 and S2, λ: λ-meter; F: ^{57}Fe foil used as a source of Mössbauer radiation; D: semitransparent avalanche photo-diode with 1 ns time resolution; A: 4 mm aperture, Si: reference silicon single crystal with (110) surface in an evacuated thermostat on a 4-circle goniometer. The distances from the APS source are given.

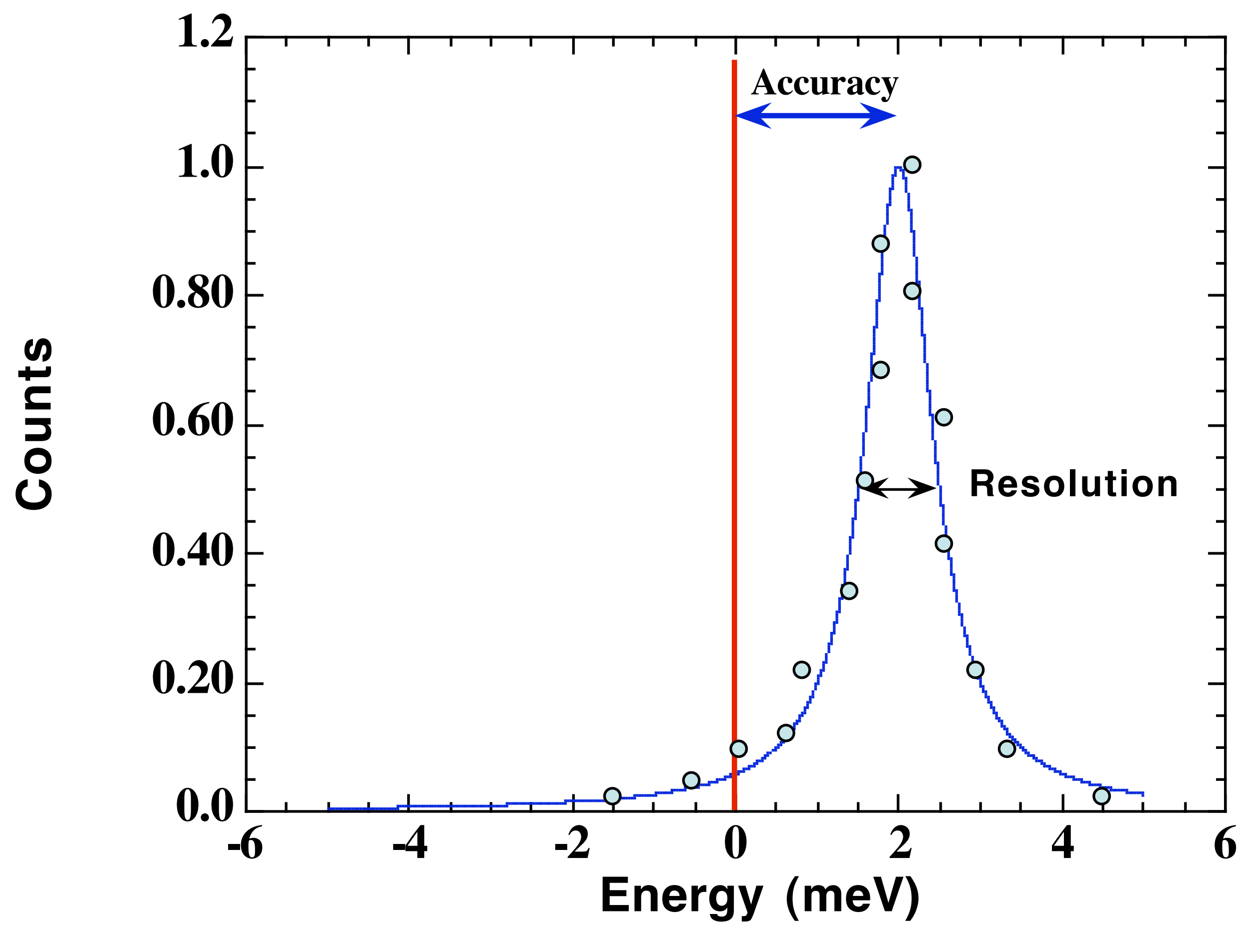
Calibration against Si lattice constant



Wavelength & energies of Mössbauer isotopes determined at a synchrotron radiation source

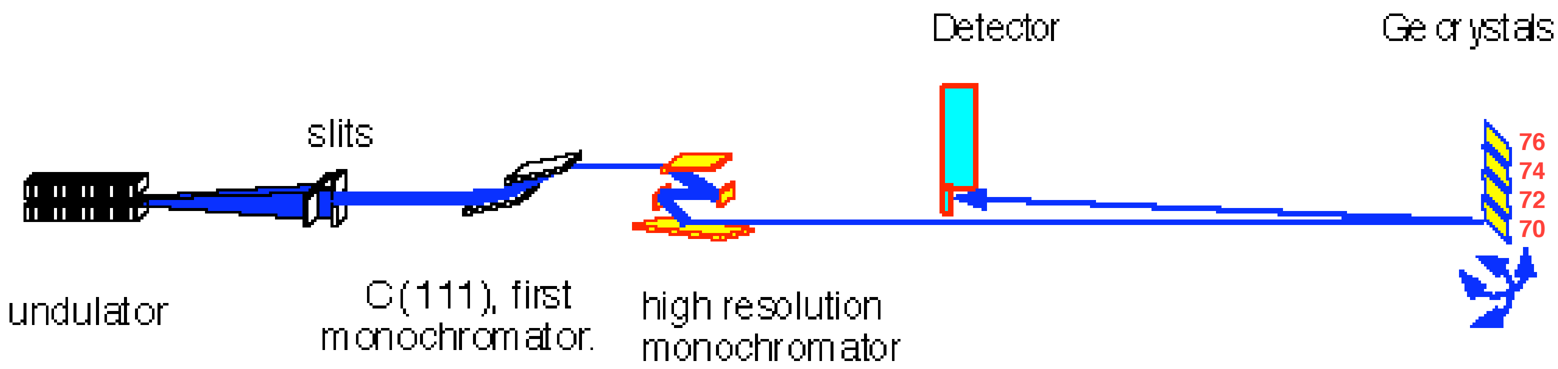
isotope	E (eV)	λ (Å)	$\delta\lambda/\lambda$ (10^{-7})
^{57}Fe	14412.497(3)	0.86025474(16)	1.9
^{151}Eu	21541.418(10)	0.57556185(27)	4.7
^{119}Sn	23879.478(18)	0.51920811(39)	7.4
^{161}Dy	25651.368(10)	0.48334336(19)	4.0

Accuracy and resolution in a measurement



Precision is related to the statistical quality of the data

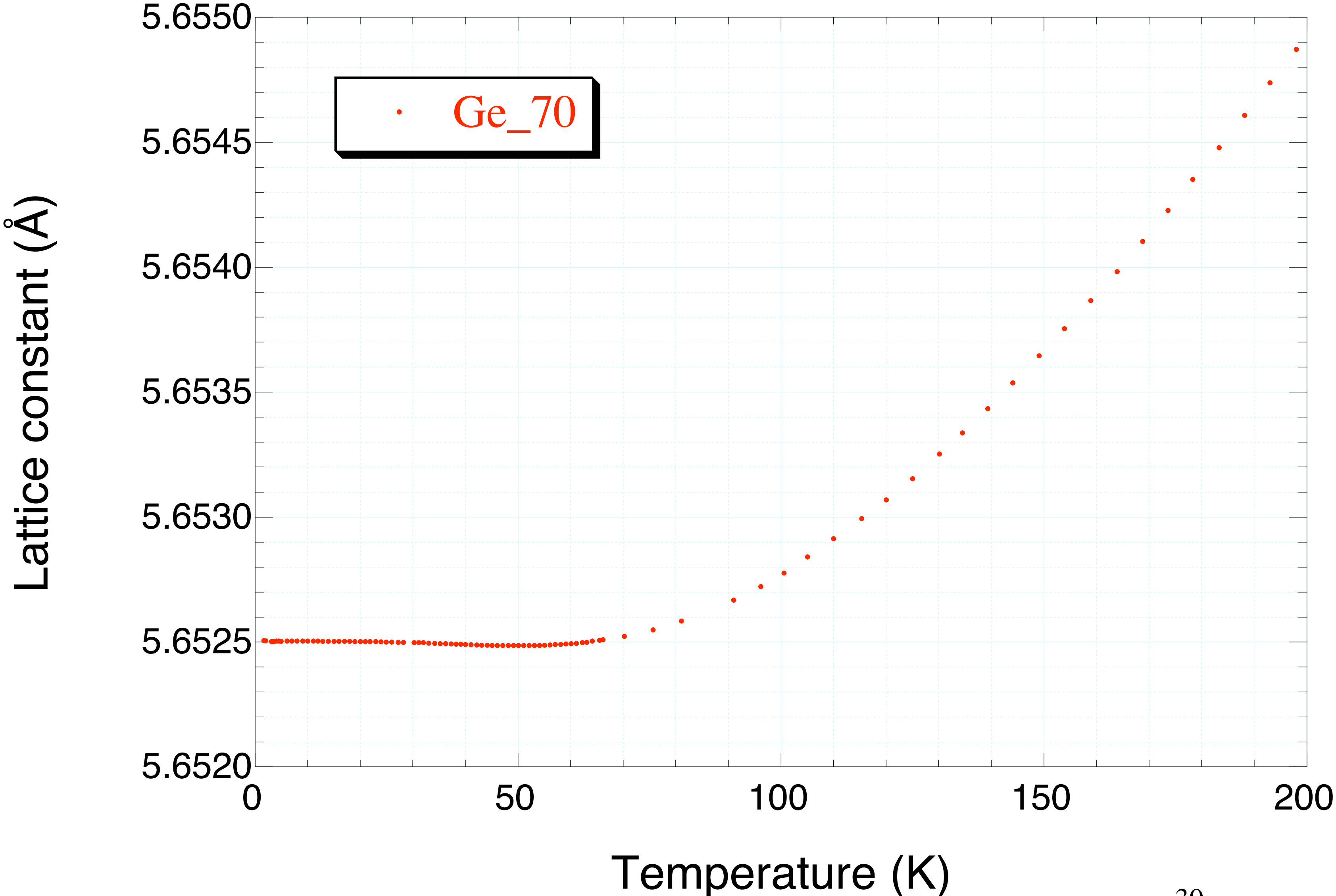
High resolution monochromators and exact backscattering

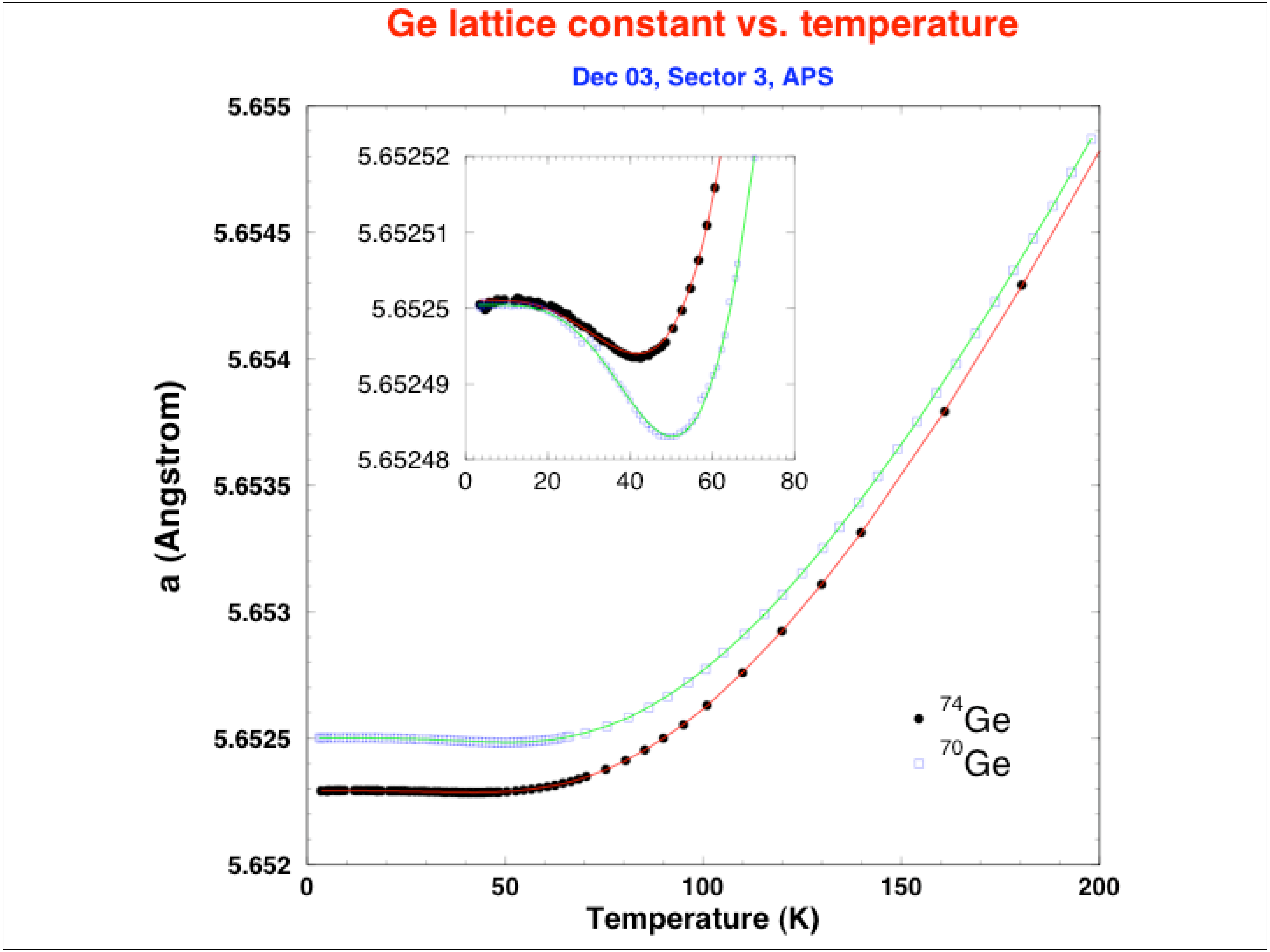


$$\lambda = 2d\,\cancel{\sin\theta}$$

$$\delta E/E_0 = -\delta d/d$$

Bragg back-scattering


Ge_70
Lattice constant (Å)
5.6550
5.6545
5.6540
5.6535
5.6530
5.6525
5.6520
0
50
100
150
200
Temperature (K)



Ge lattice constant vs. temperature
Dec 03, Sector 3, APS
a (Angstrom)
Temperature (K)
5.655
5.6545
5.654
5.6535
5.653
5.6525
5.652
0
50
100
150
200
5.65252
5.65251
5.6525
5.65249
5.65248
0
20
40
60
80
74Ge
70Ge

Isotope effect is observed in

Superconductivity

Ferroelectricity

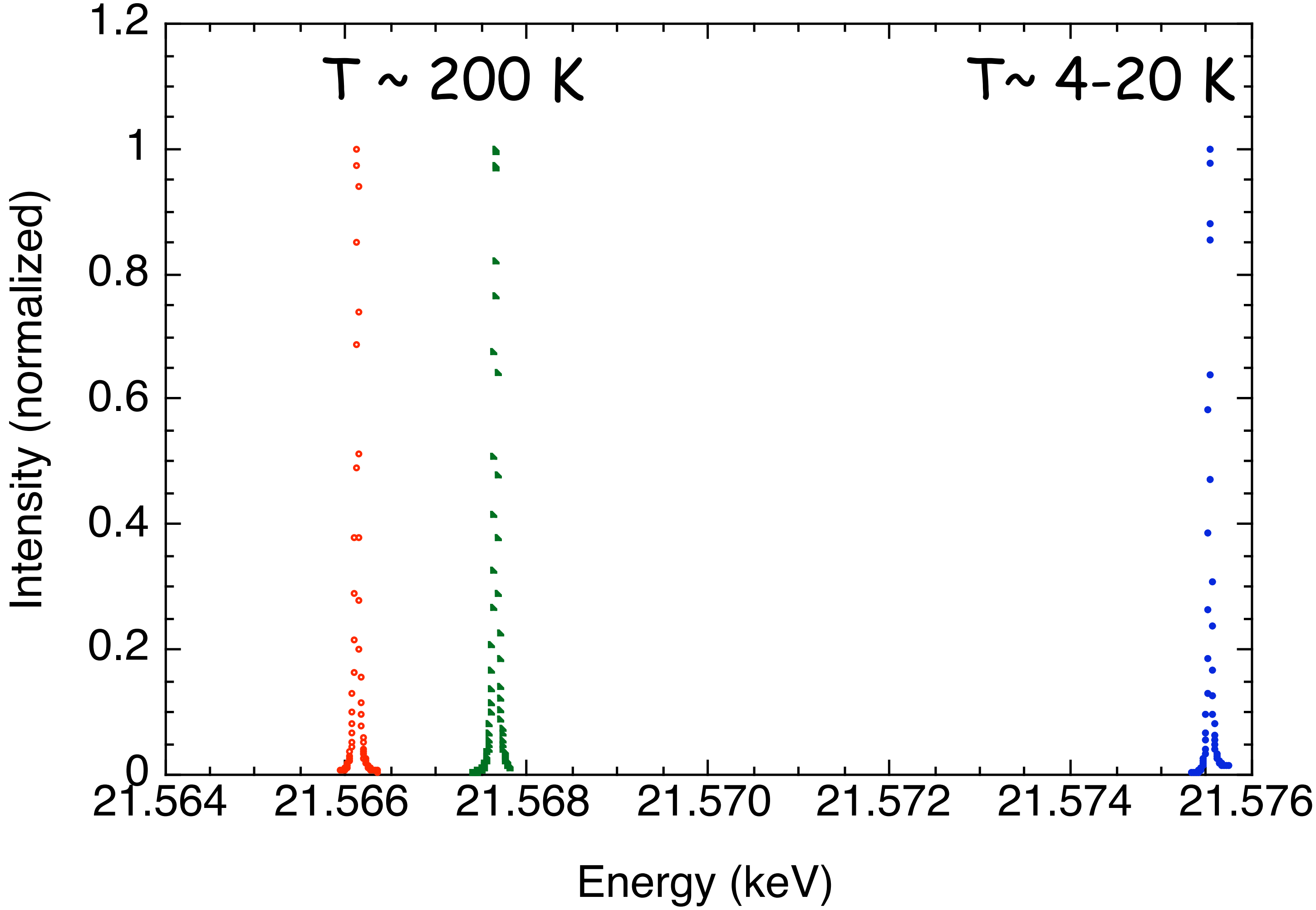
Magnetoresistance

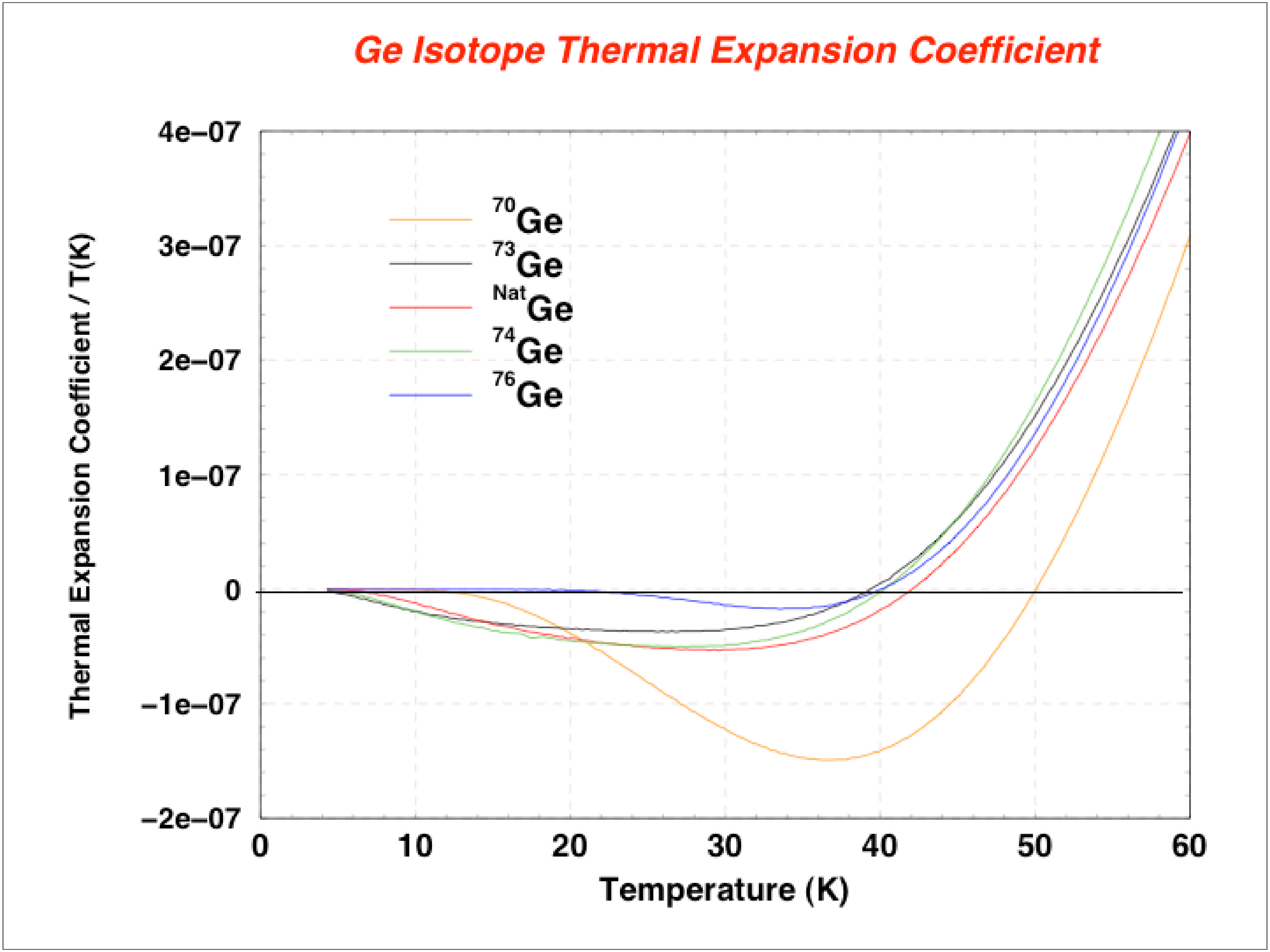
Metal-Insulator transition

Thermal conductivity

Thermoelectric power

Typical data sets





Ge Isotope Thermal Expansion Coefficient
70Ge
73Ge
NatGe
74Ge
76Ge
4e−07
3e−07
2e−07
1e−07
0
−1e−07
−2e−07
0
10
20
30
40
50
60
Temperature (K)
Thermal Expansion Coefficient / T(K)

Lattice constants of Ge

M	a_0(Å)	T(K)	M (amu)
70	5.652521	8-21	70.04953
73	5.652421	8-60	72.90906
74	5.652336	10.3	73.85475
76	5.652267	9.8	75.38534

M. Hu, et al, Phys. Rev. B (67) 113306 (2003)

High Resolution Monochromators

What is the state of the art in high resolution in the hard x-ray regime ?

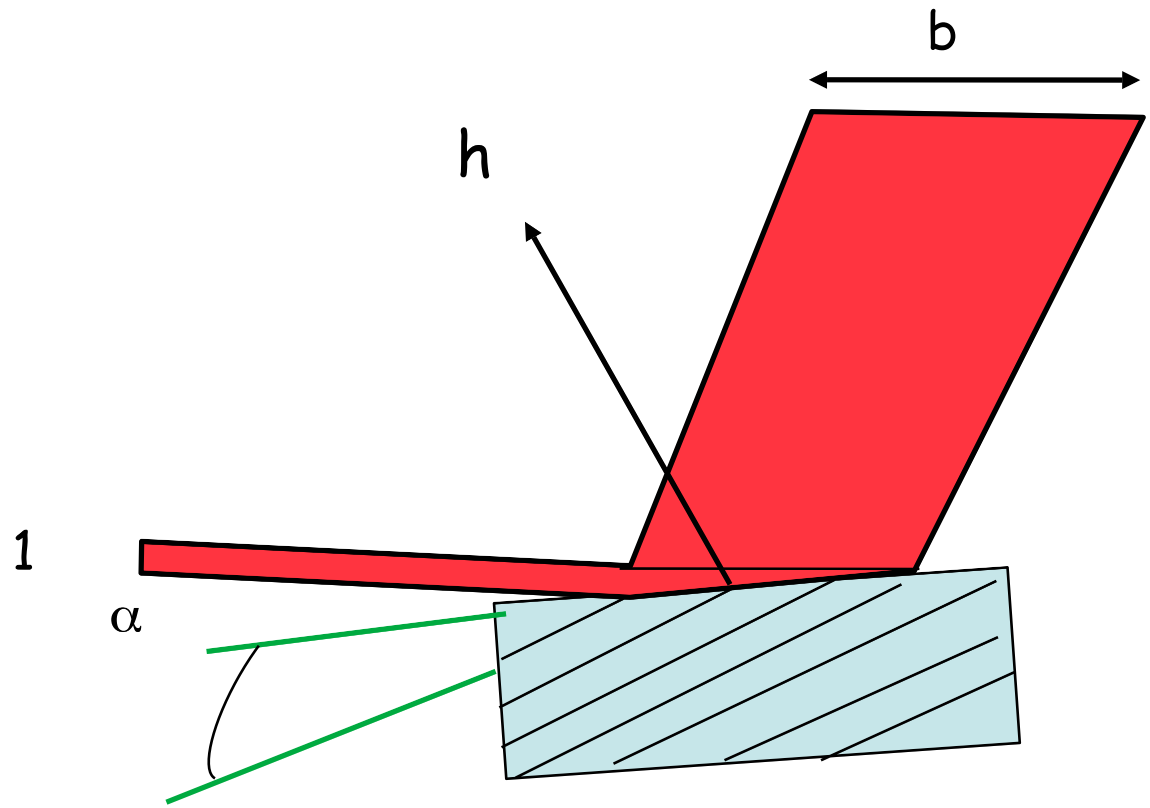
Resolution power, $R = E/\Delta E$

$7 < E < 30$ keV

$10^{-9} < \Delta E < 10^{-3}$ eV : nano-eV / meV

$10^{7} < R < 10^{13}$

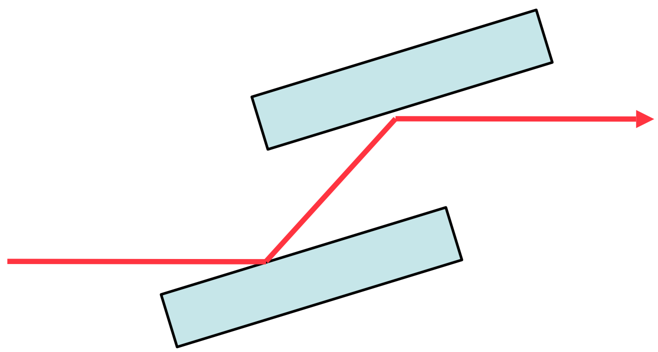
The beamlines 3-ID at the APS are built for this energy range to study collective excitations in condensed matter and hyperfine interactions for nuclear resonance scattering



$$\boldsymbol{b} = -\frac{\sin(\theta_B - \alpha)}{\sin(\theta_B + \alpha)}$$

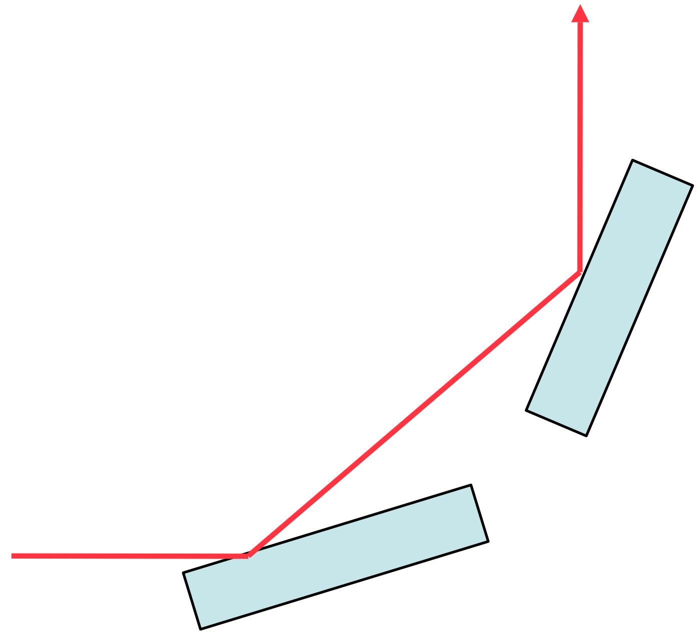
$0.05 < b < 50$

Collimation by asymmetric Bragg diffraction



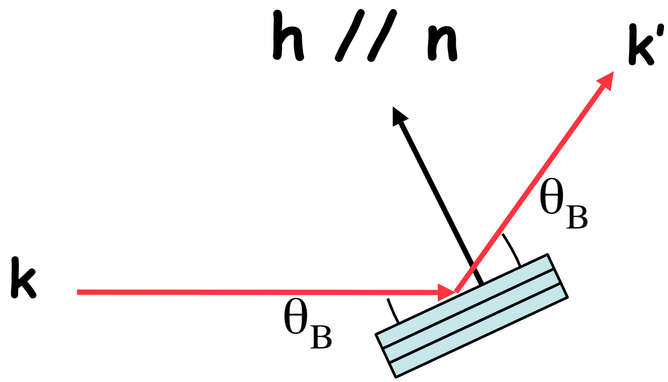
non-dispersive: (+ -)

Does not select energy per se
Beam leaves in the same direction

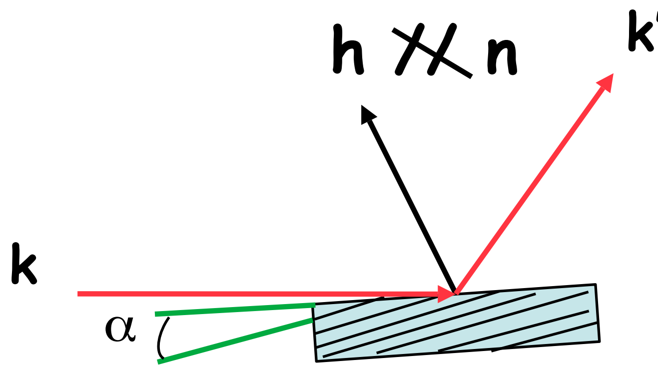


dispersive: (+ +)

energy selective, beam
Leaves in a different direction



Symmetric: Bragg planes are parallel to the surface of the crystal

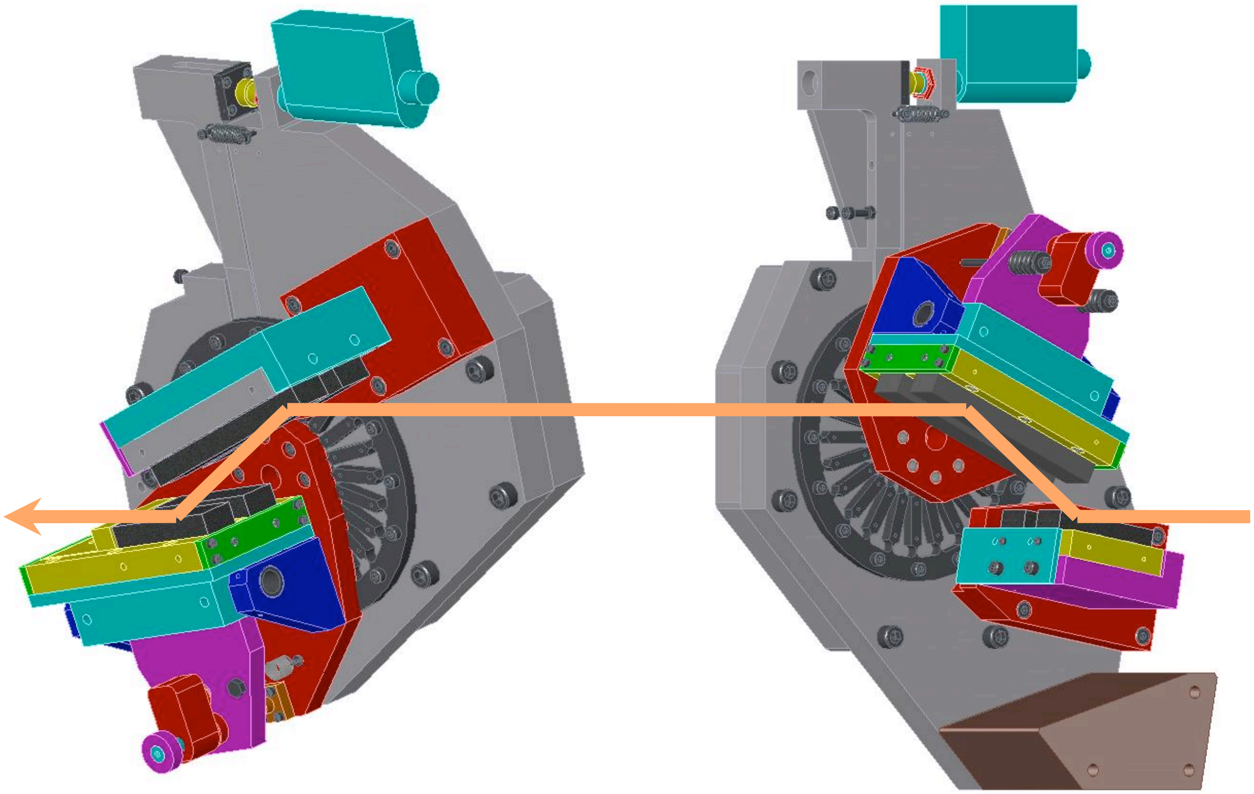


Asymmetric, Bragg planes are not parallel to the surface of the crystal

$$b = -\frac{\sin(\theta_B - \alpha)}{\sin(\theta_B + \alpha)}$$

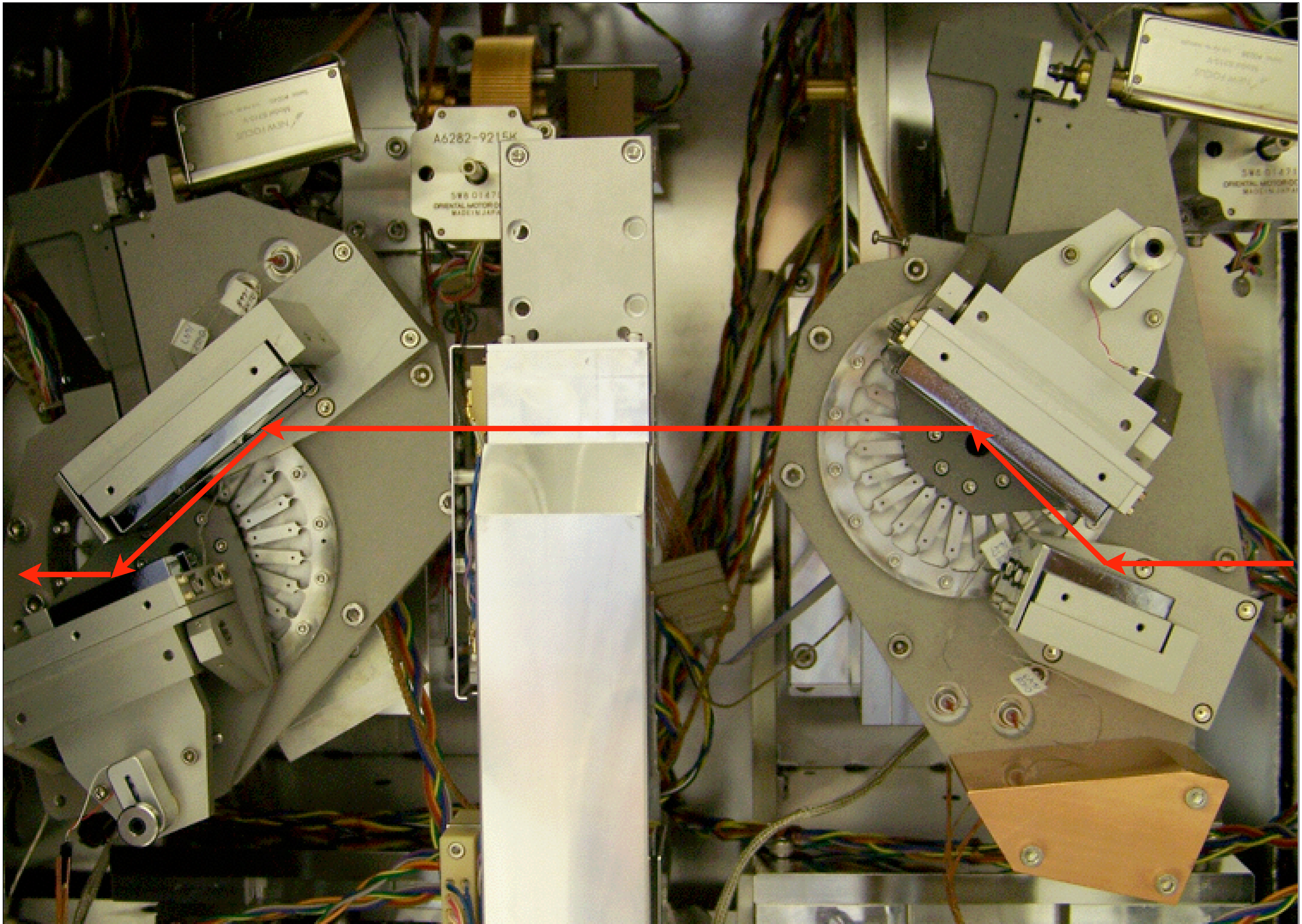
b < 1	asymmetric,	beam enlarges
b = 1	symmetric,	α = 0
b > 1	asymmetric	beam shrinks

MERIX Monochromator



Two pairs of Si (220) and Si (400) crystals are aligned side by side
to provide ~ 20, 50, 70, and 120 meV resolution over 5-15 keV range.

The Kohzu K15M stages capable of rotating 360 degrees with 35 μrad coarse resolution, and 0.025 microradian fine resolution over 2 degrees. This is a new design with a solenoid clutch mechanism to decouple coarse and fine motions.


A6282-9215K

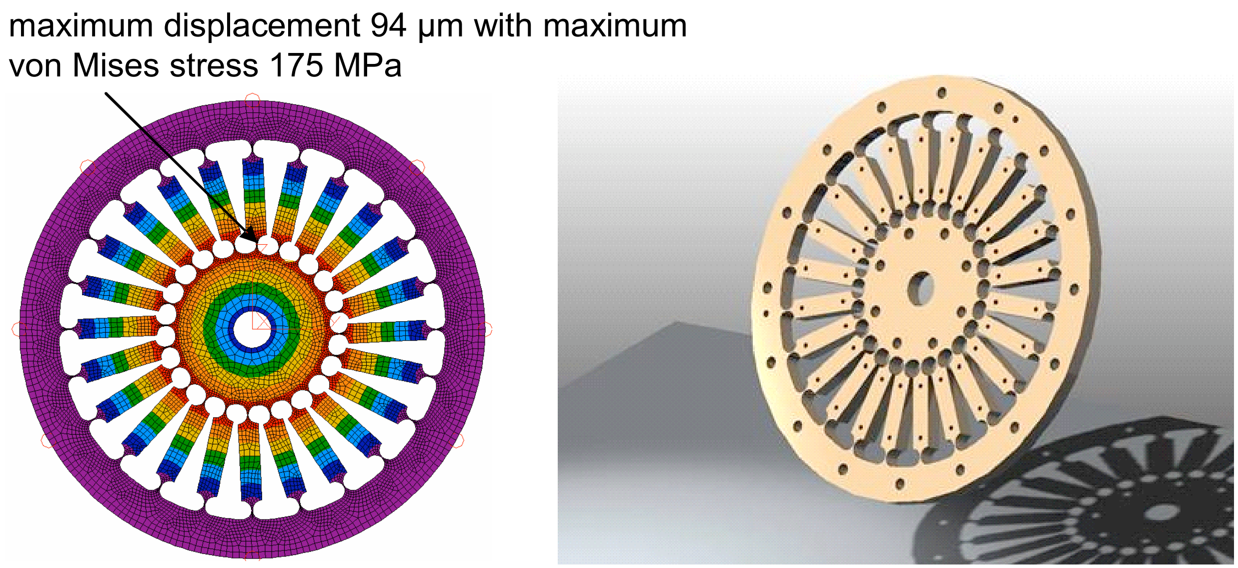


Fig. 1. *Left: A finite-element simulation for a wheel-shaped rotary weak-link module. It shows the displacement distribution under a 0.89 Nm torsion load on the center part while the outer ring is fixed on the base. Right: A 3-D model of a typical overconstrained rotary weak-link module. It consists of 16 layers of stainless-steel weak-link sheets bonded together with a total thickness of 4 mm.*

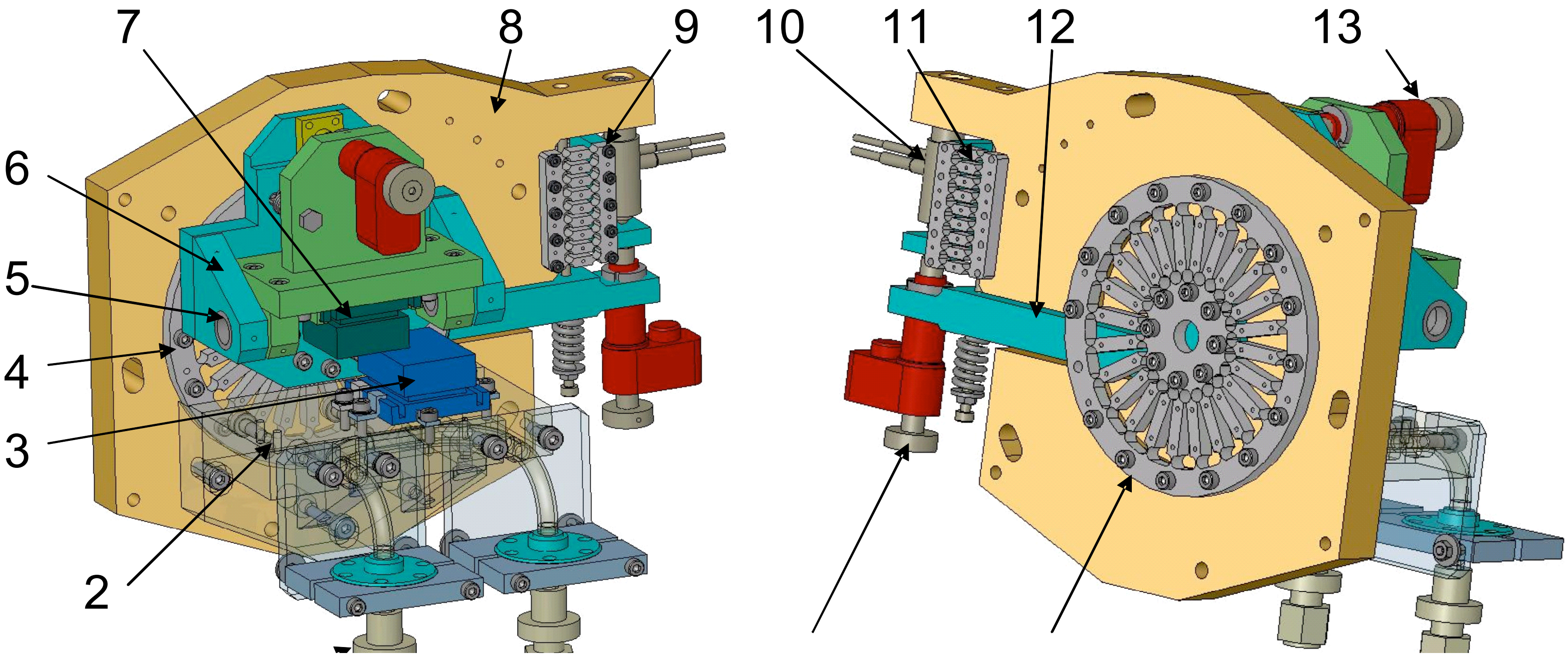
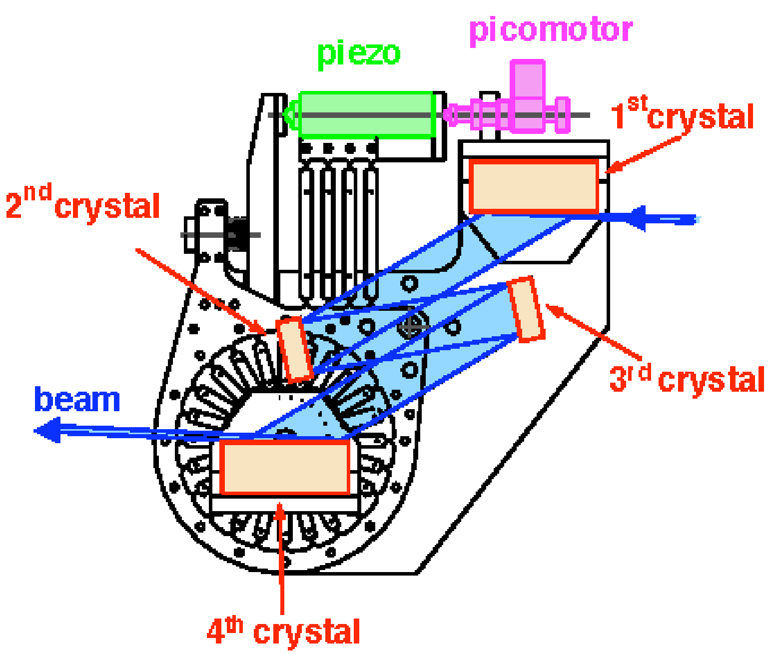
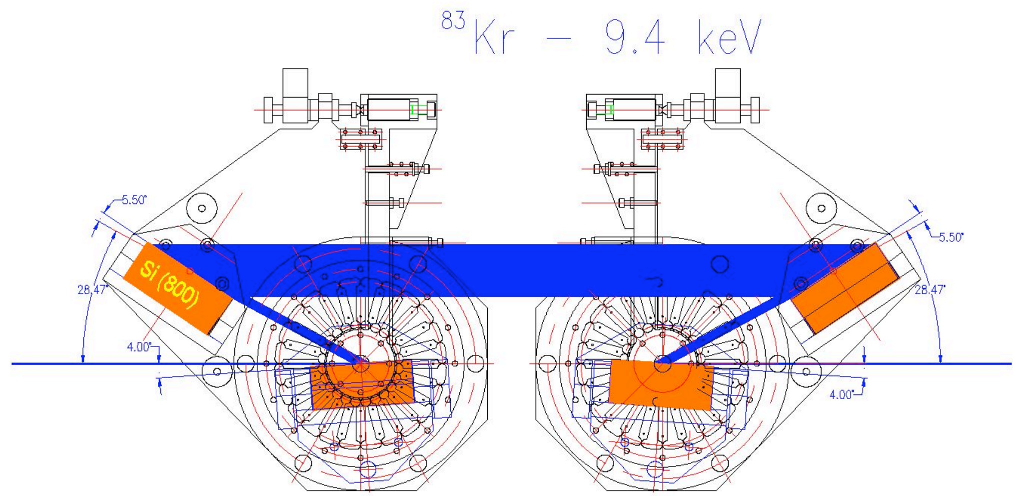


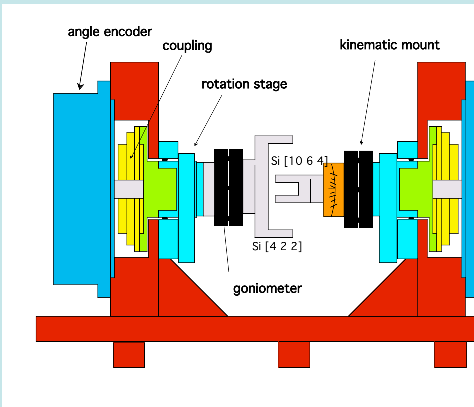
Fig. 2. *Front side and back side views of a 3-D model for a typical high-stiffness weak-link mechanism for an "artificial channel-cut crystal". (1) Cooling tube; (2) First crystal holder; (3) First crystal; (4) and (14) Rotary weak-link modules; (5) flexure bearing; (6) Second crystal holder; (7) Second crystal; (8) Base plate; (9) and (11) linear weak-link modules; (10) PZT actuator; (12) Sine bar: (13) and (15) Picomotor^{TM} actuators.*

New monochromators with artificially linked, dispersive channel-cut configuration

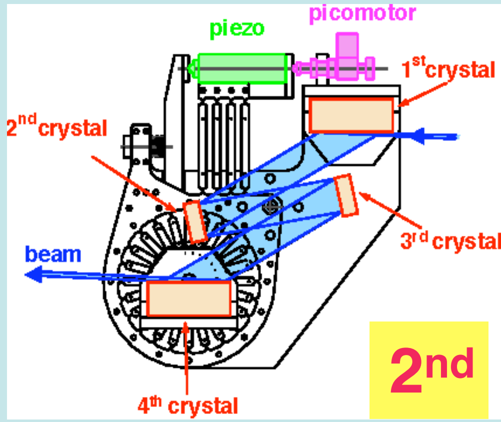




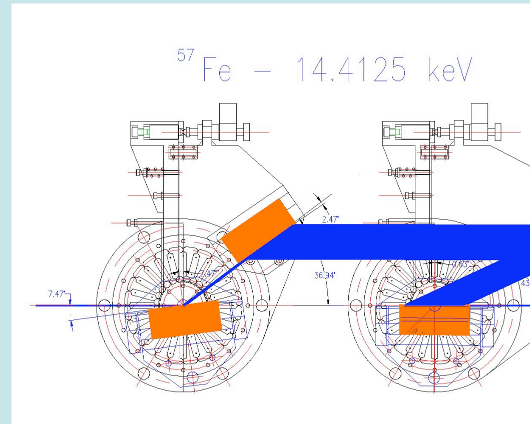
Generations of high resolution monochromators



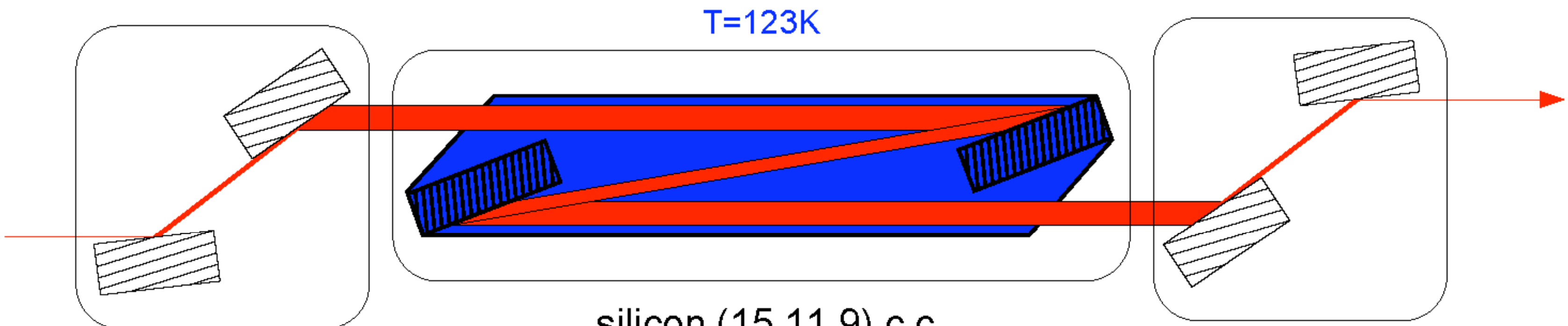
1st



2nd



3rd



2x silicon (2 2 0)
w/ weak-link ass'y

silicon (15 11 9) c.c.
mounted on cryostage

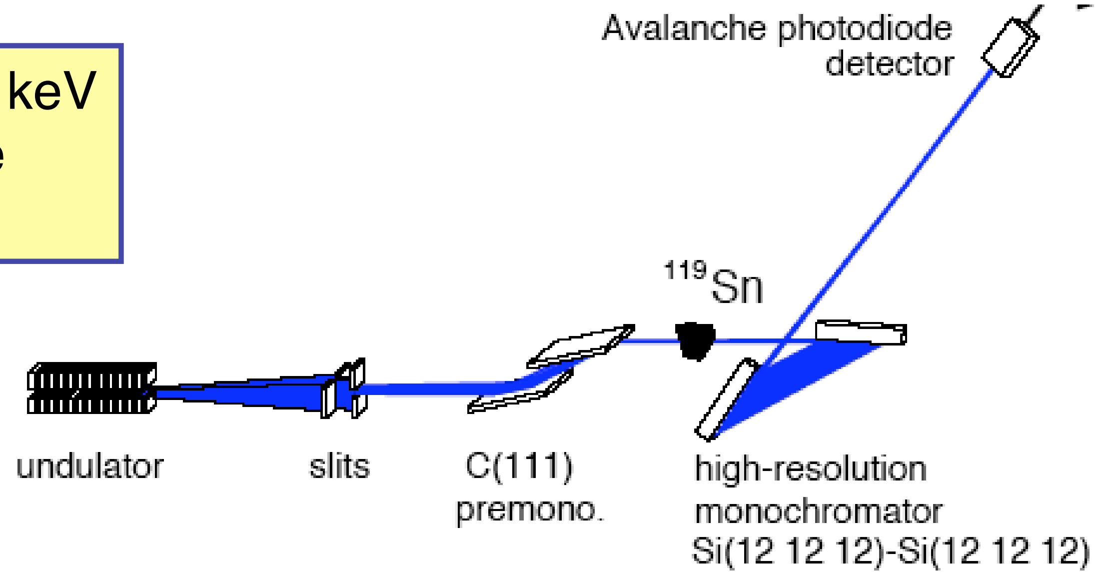
2x silicon (2 2 0)
w/ weak-link ass'y

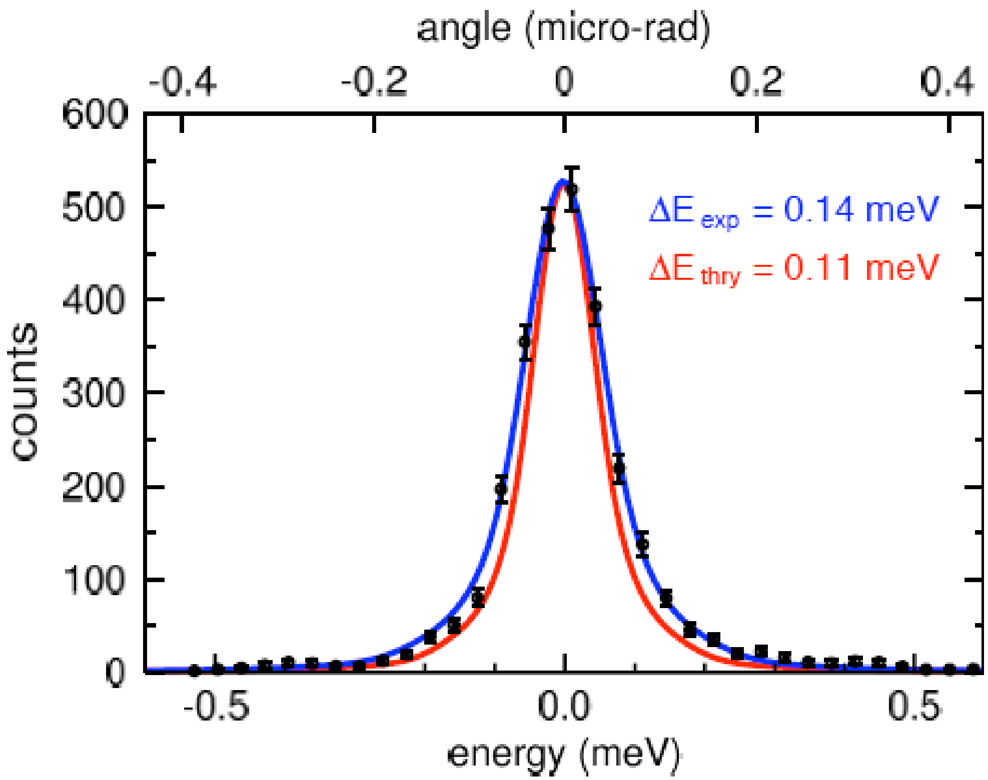
HERIX Mono for 23.72 keV, ΔE ~ 1 meV

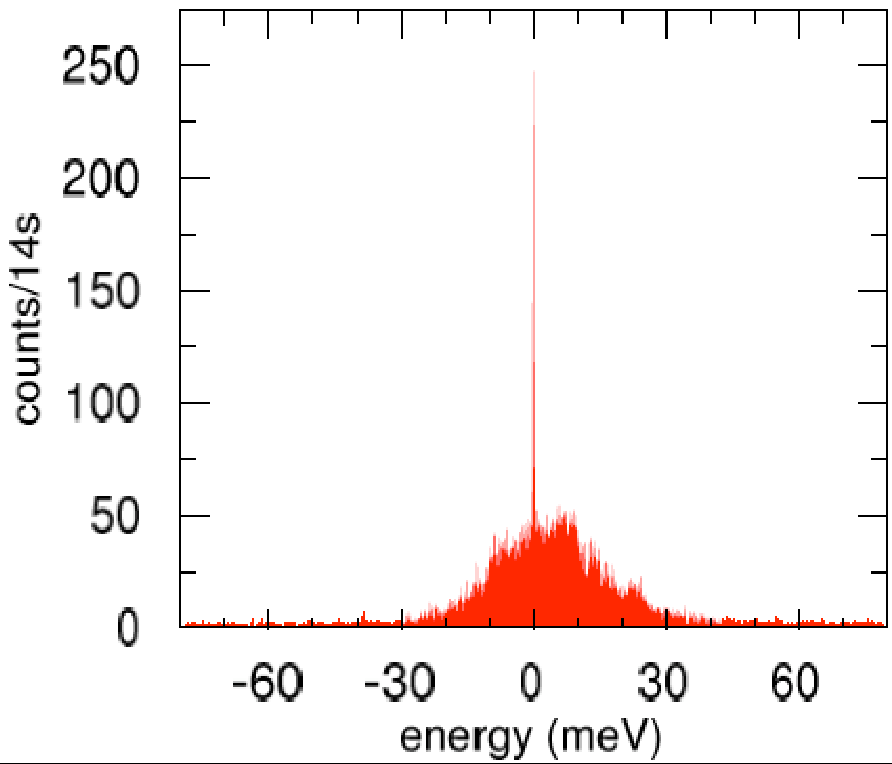
4th

Record resolution at 23.870 keV
^{119}Sn nuclear resonance
T. Toellner, 2003

$$E/\Delta E = 1.7 \cdot 10^{8}$$

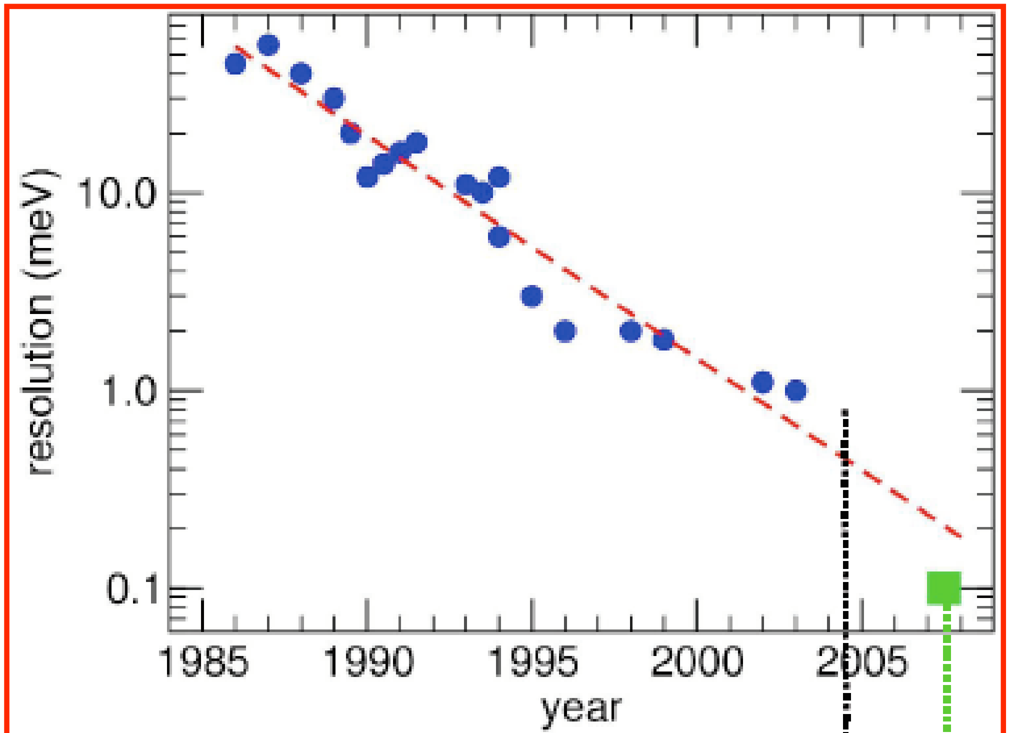


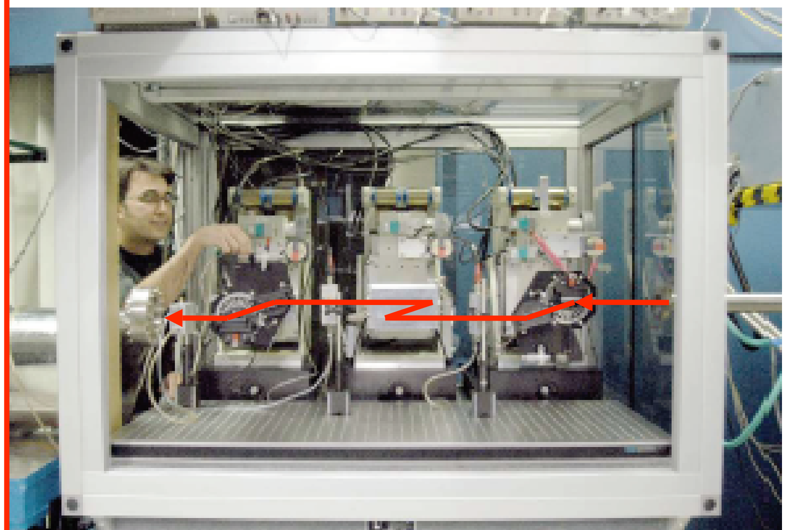


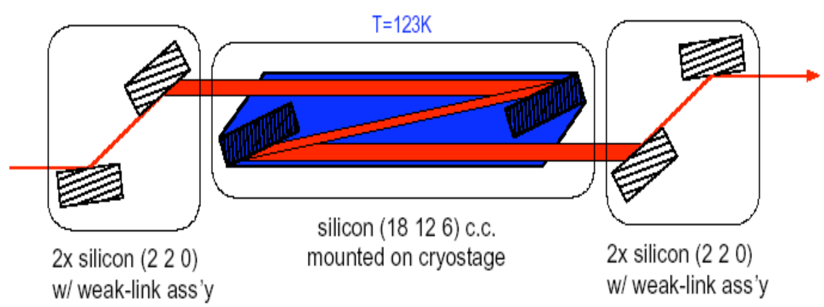


Delivered to : SRI-CAT, Advanced Photon Source,
Argonne National Laboratory.

10 kg load,
angular resolution ~5 nano-radian,
angular range: ± 2.5° range







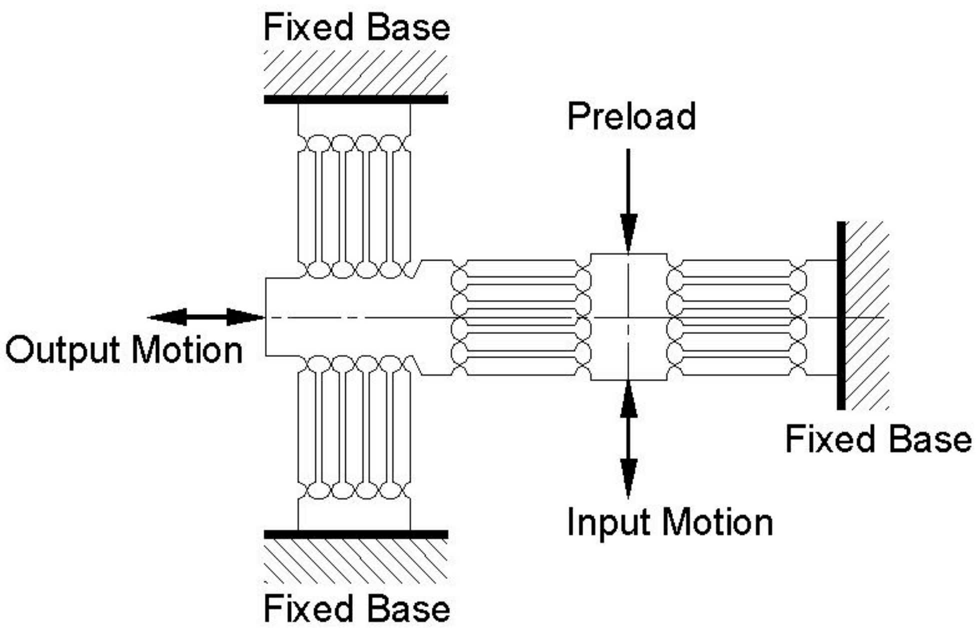
Where is the limit on silicon Based monochromatization techniques ?

We believe one can achieve 0.1 meV at 15 keV.

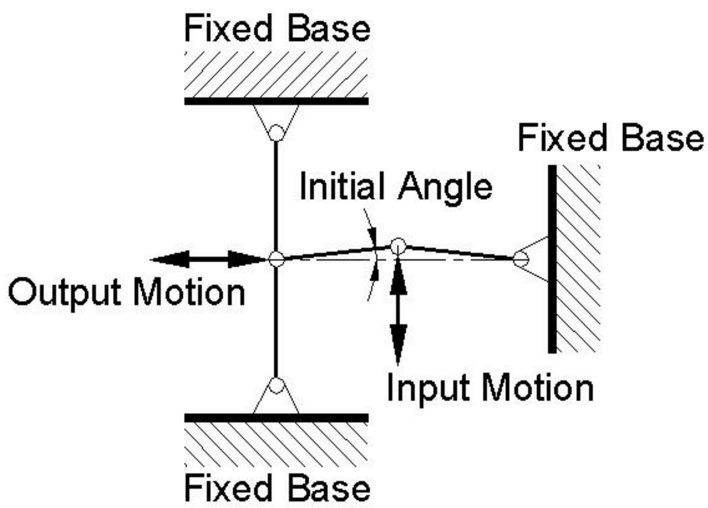
However, higher energy limits above 30 keV needs to be further developed.

4th

High stiffness / weak-link nano-positioners



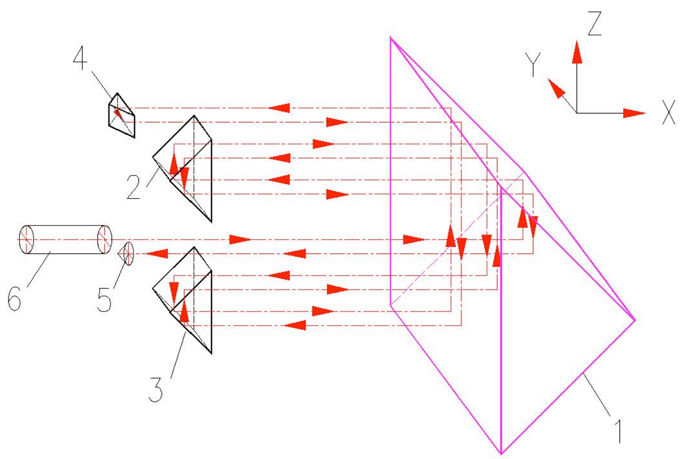
(a)

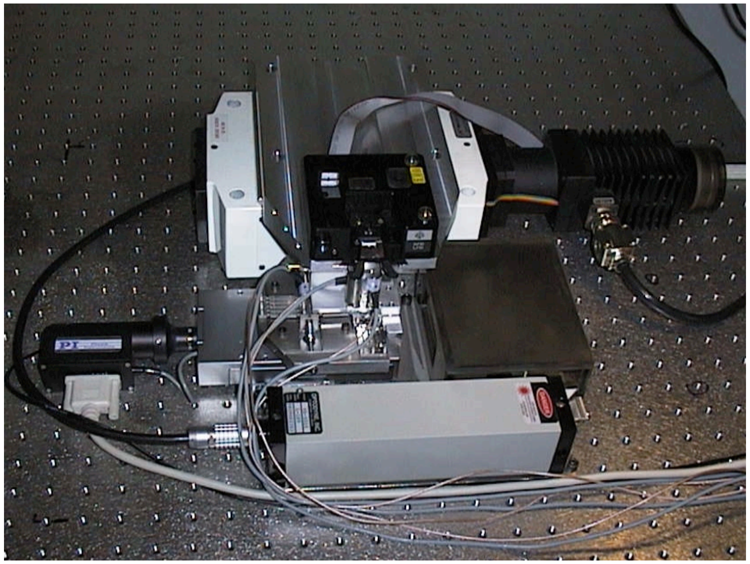


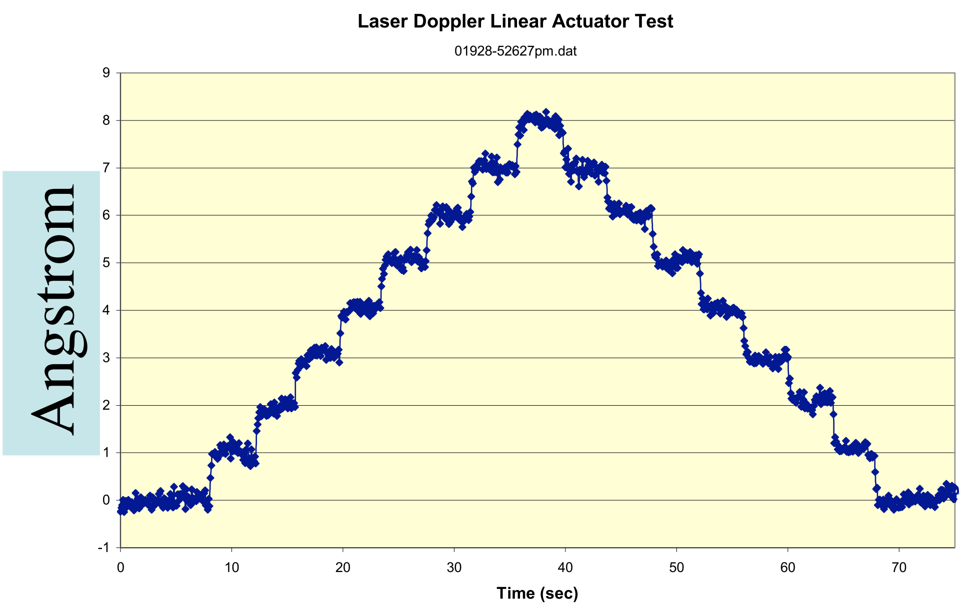
(b)

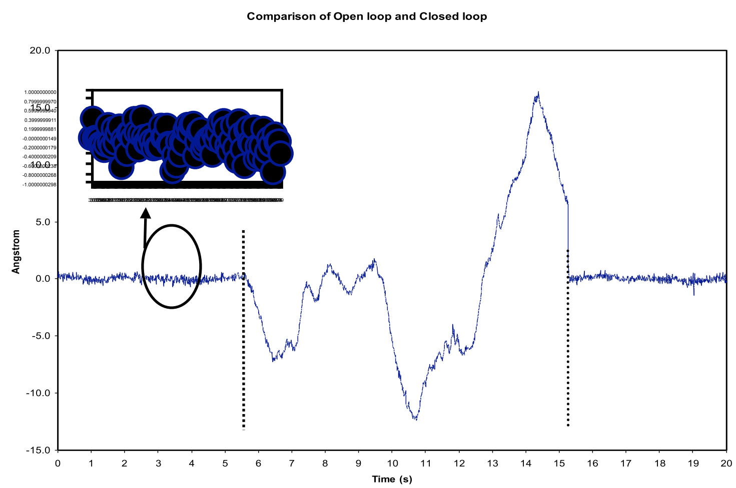
D. Shu, Y. Han, T. Toellner, E. E. Alp, SPIE (2002)

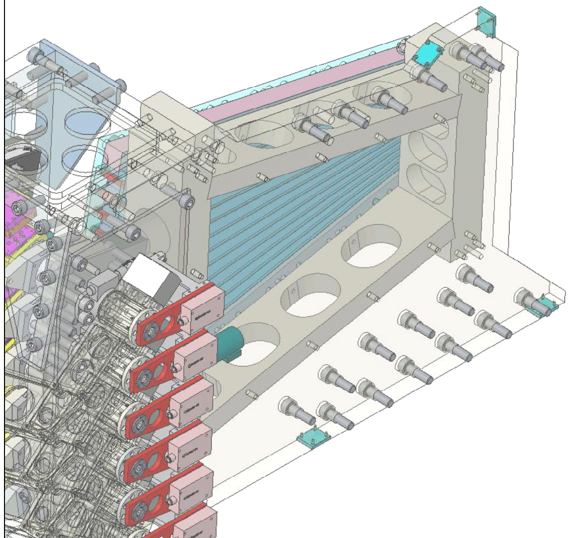
LDLA: Laser Doppler Linear Actuator, (D. Shu)

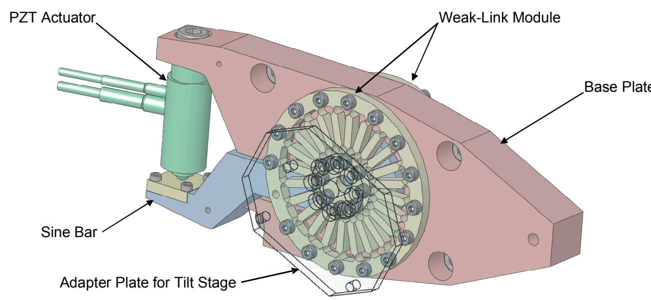


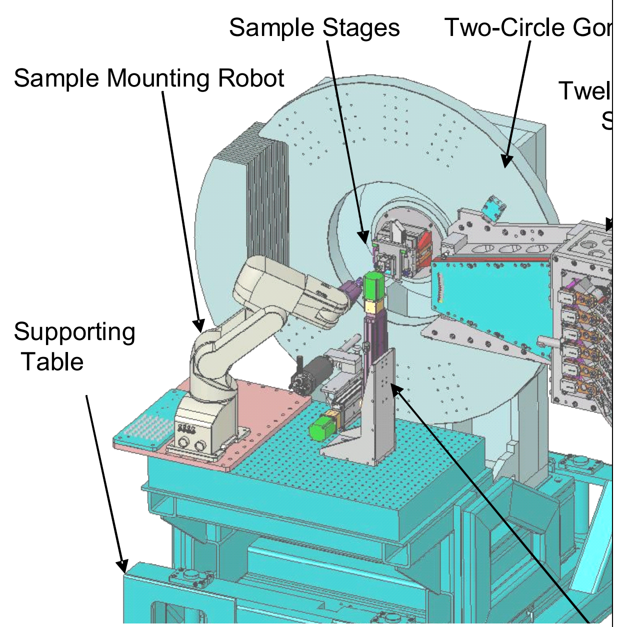




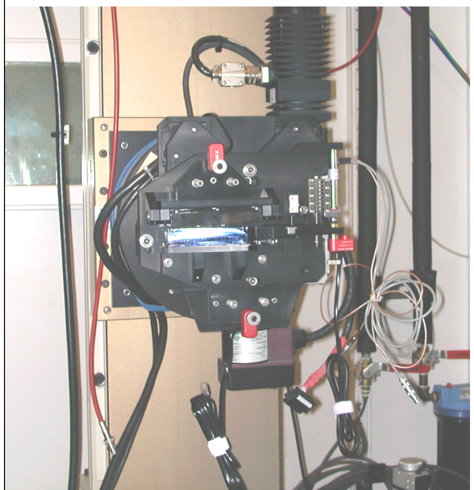


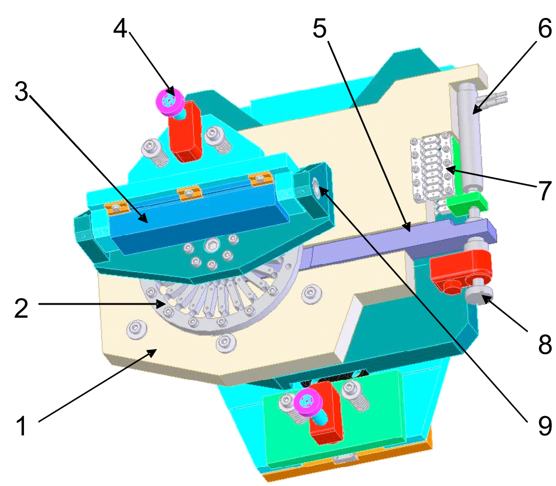


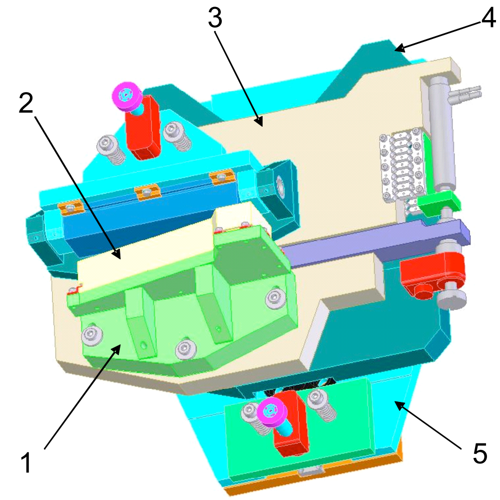




3-D models of the analyzer array for the x-ray powder-diffraction instrument at APS XOR sector 11.



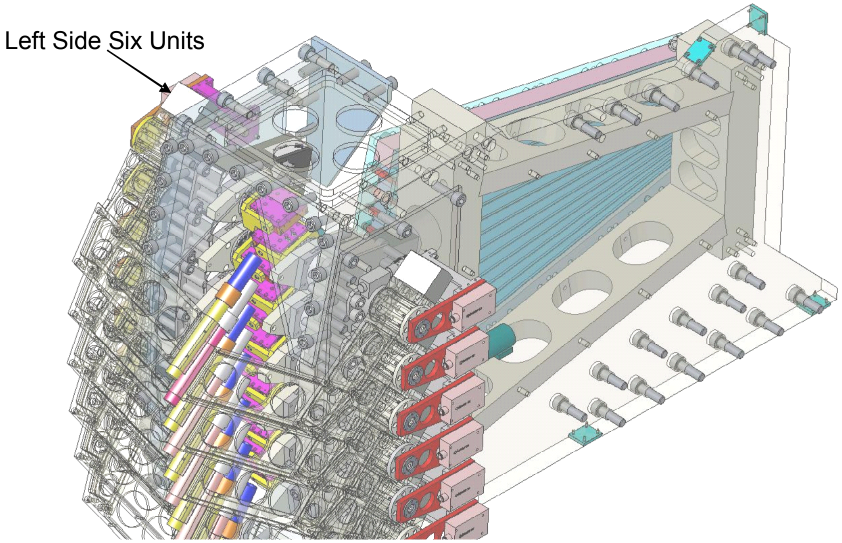


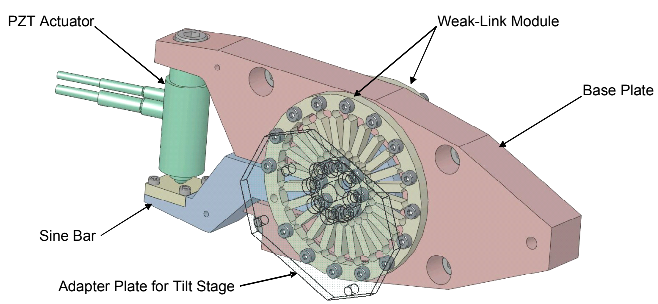


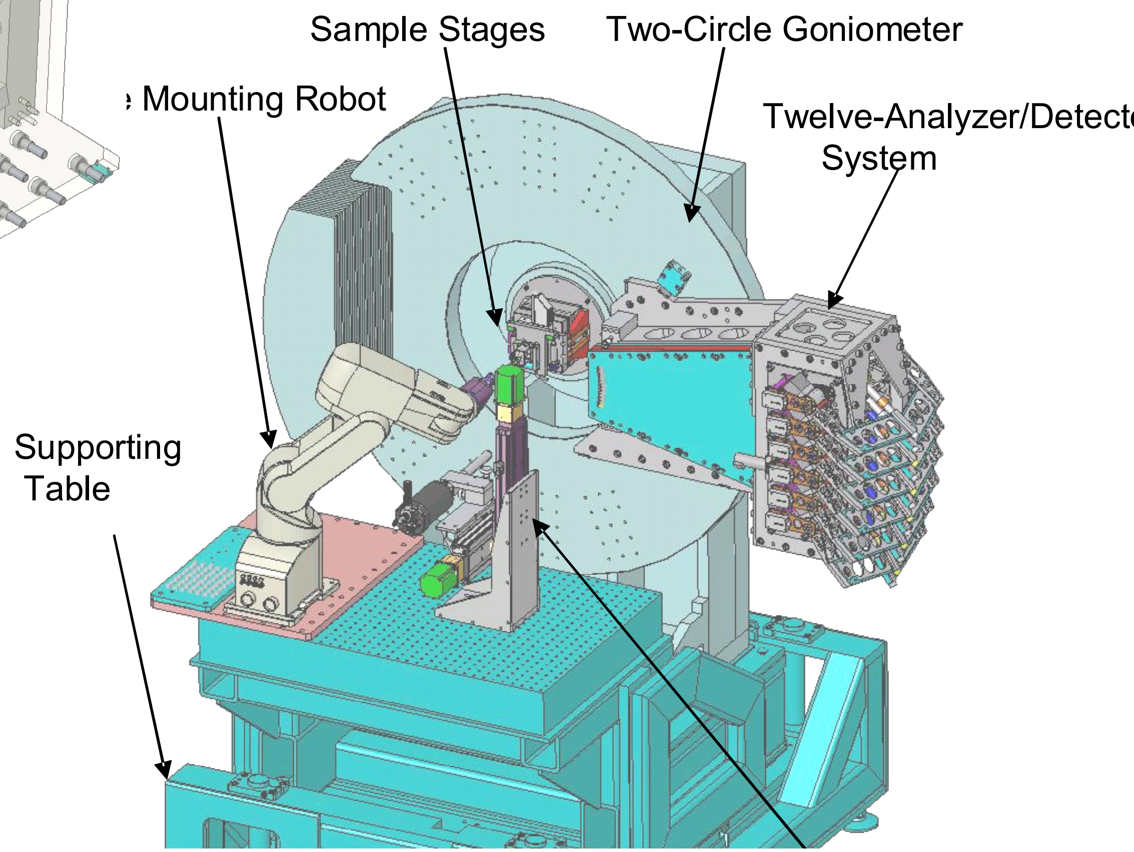
Right: photograph of a laminar weak-link mechanism for the high-resolution crystal analyzer mounted on a main rotary stage for NIST ultra-small-angle x-ray scattering instrument at the APS XOR/UNICAT sector 33.

Middle:The design of the artificial channel-cut crystal mechanism which includes: (1) base plate; (2) weak-link module acting as a planar rotary shaft; (3) second crystal; (4) PicomotorTM actuator; (5) sine-bar; (6) PZT actuator; (7) weak-link module acting as a linear stage; (8) PicomotorTM actuator; (9) flexure bearing. The first crystal and its holder are not shown in this figure.

Left: The design of the artificial channel-cut crystal mechanism with first crystal (2), its holder (1), and base plate (3). The entire artificial channel-cut crystal mechanism is kinematically mounted on a Picomotortm driven roll alignment structure (5) through three commercial magnetic couplers (4).







3-D models of the analyzer array for the x-ray powder-diffraction instrument at APS XOR sector 11.

<u>Must have</u>

1) Crystal manufacturing and characterization laboratory complete with x-ray machines and topography, crystal orientation, and rocking curve measurements,

2) A research-grade machine shop complete with cutting, high speed dicing, ultrasonic drilling, lapping, and polishing machines for different sizes of crystals from a few mm to a meter.

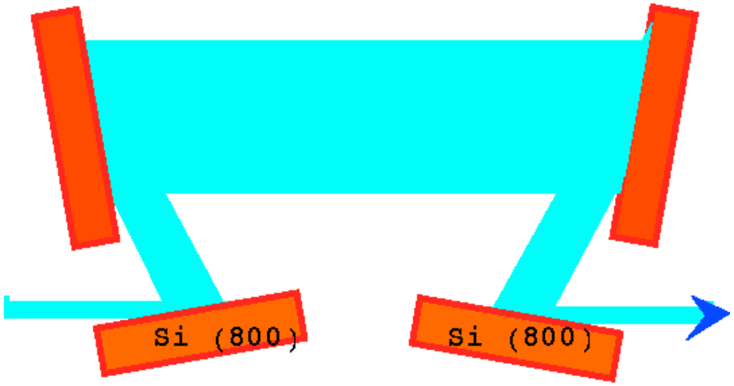
3) X-Ray reflectivity lab for thin film optics

4) Thin film coating & multilayer coating facilities

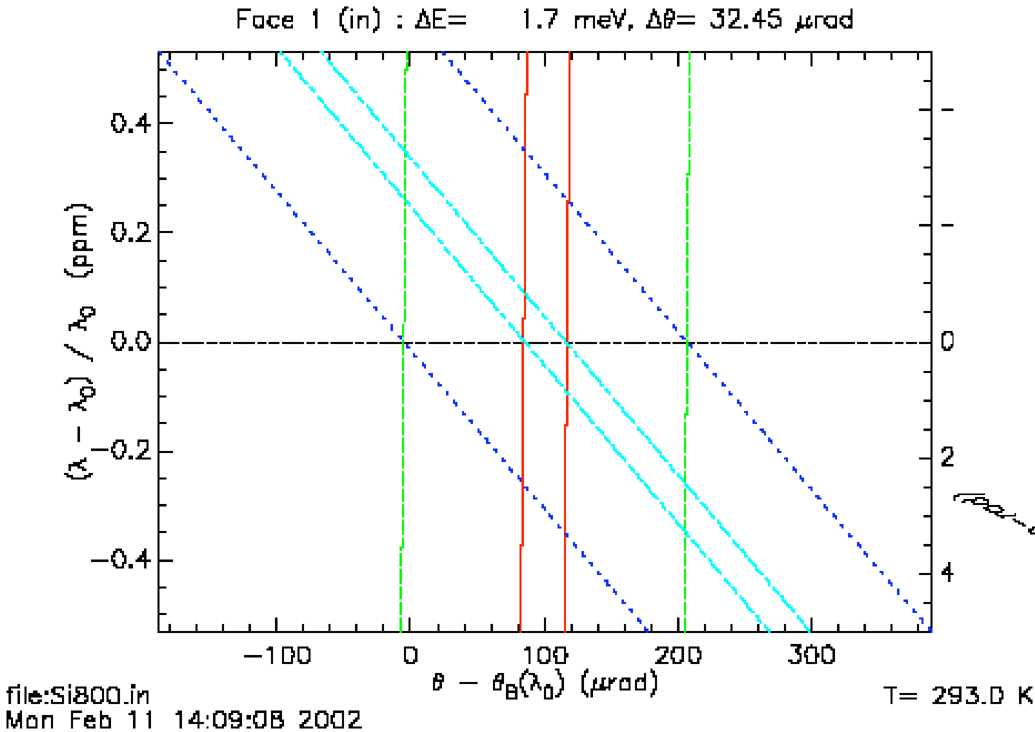
5) Visible light metrology (a la L. Assoufid, ANL)

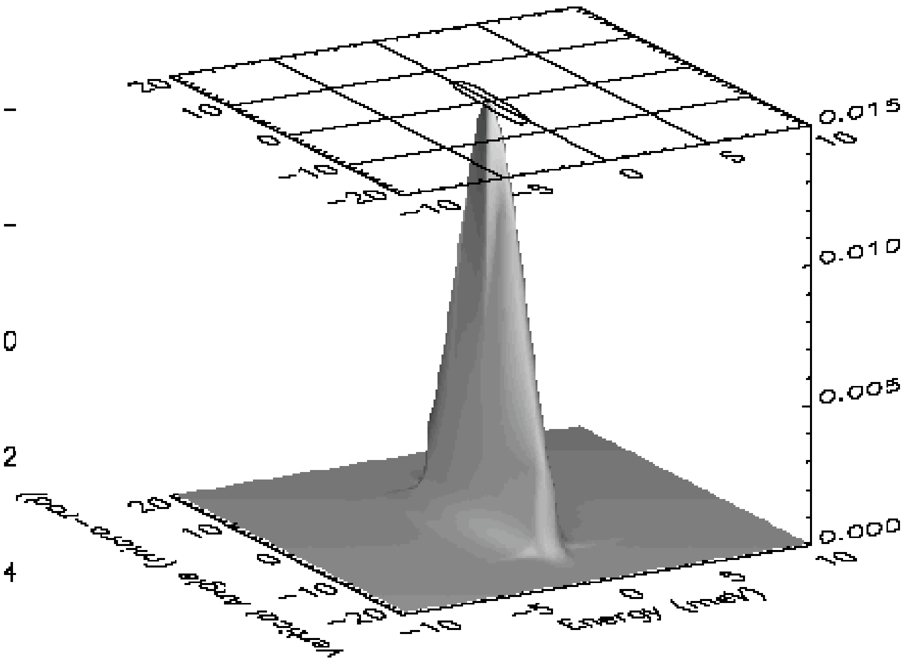
6) Technical staff that are under the control of division, not “the central shops”

Si (800), 4 crystal set for 9.4 keV

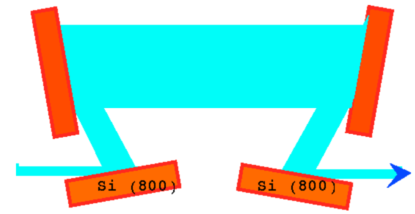


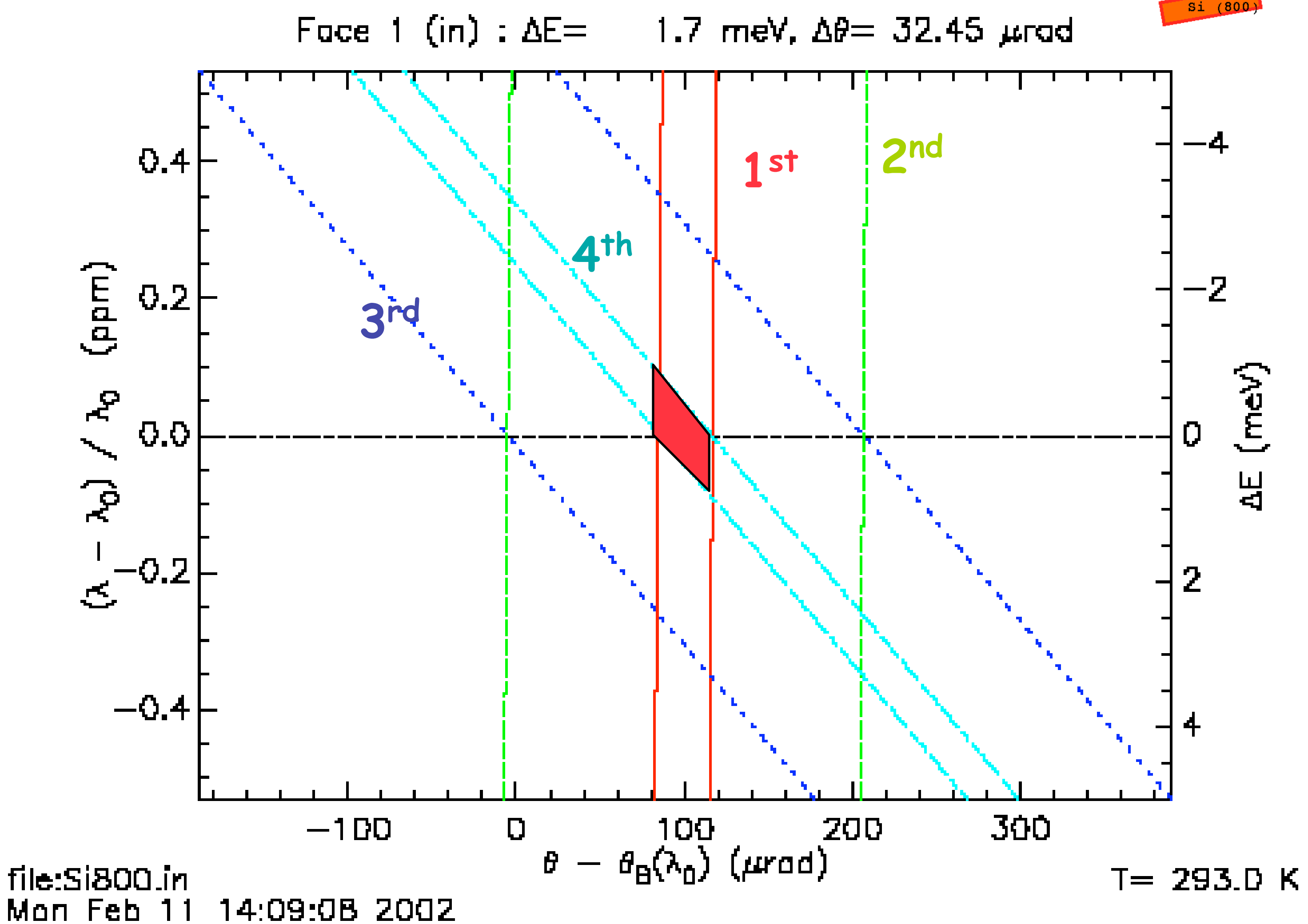
ΔE = 0.97 meV,
ΔΘ=32 μrad





DuMond diagram (J. DuMond, 1932)



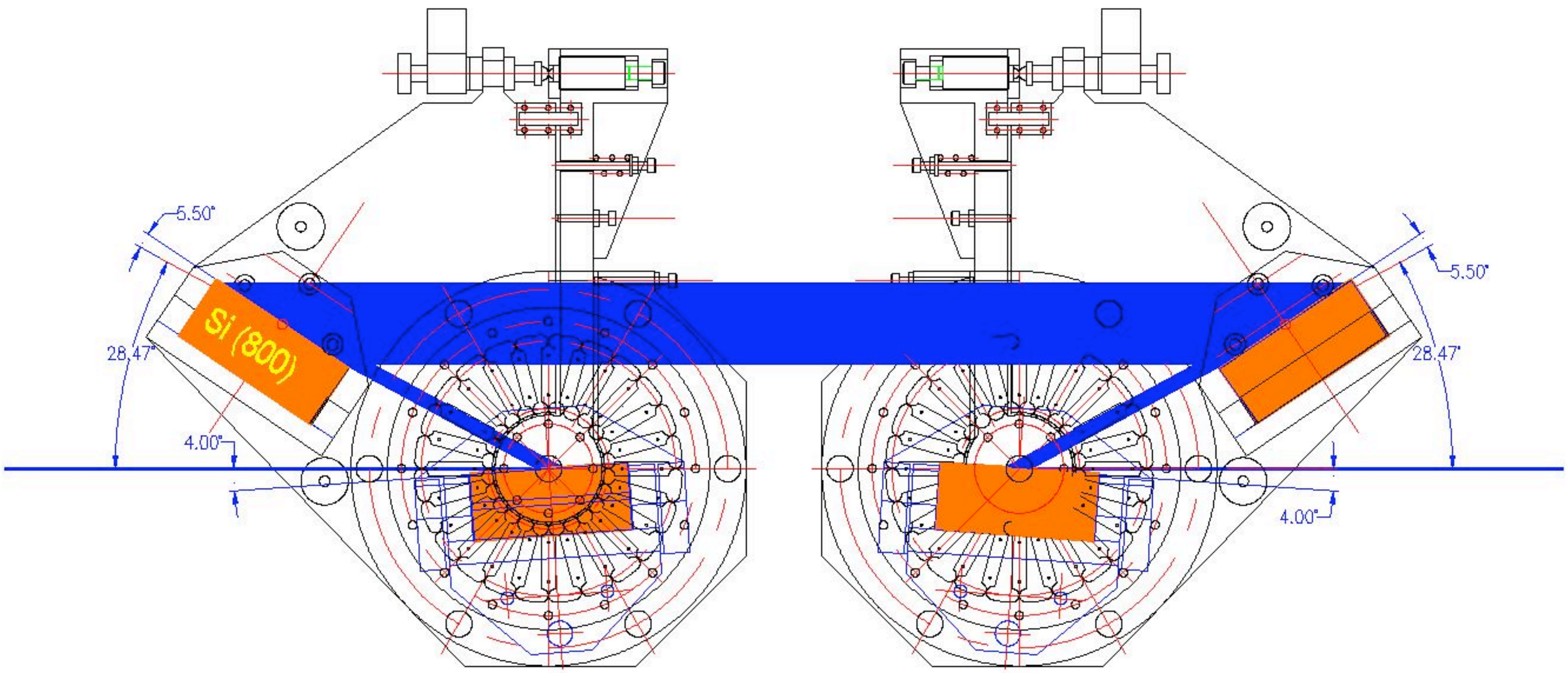


Energy deviation from Bragg energy

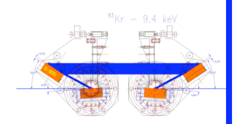
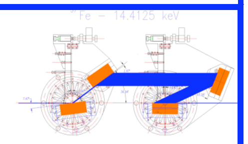
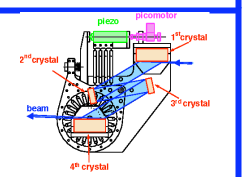
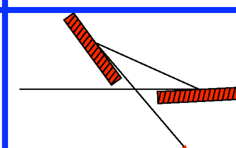
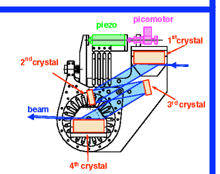
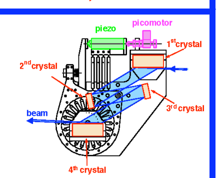
Angular deviation from Bragg angle

New monochromators with artificially linked, dispersive channel-cut configuration

^{83}Kr, E= 9.401 keV, ΔE= 1.0 meV



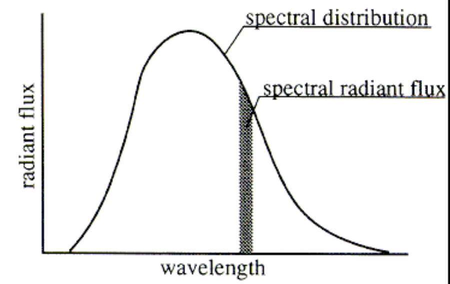
Monochromators

Isotope	Energy (keV)	ΔE (meV)	Flux (GHz)	Type
^{83}Kr	9.4035	1.0	6	
^{57}Fe	14.4126	1.0	1.2	
IXS ^{151}Eu	21.65 21.54	0.7 0.8	0.8 0.4	
^{119}Sn	23.879	0.14	0.004	
^{119}Sn	23.879	0.85	0.2	
^{161}Dy	25.6514	0.5	0.1	

Radiometry is the field that studies the measurement of electromagnetic radiation

Radiant energy Q_e

The energy carried by electromagnetic radiation

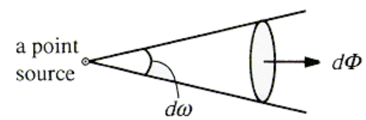


Radiant flux Φ

Radiant energy transmitted per unit time

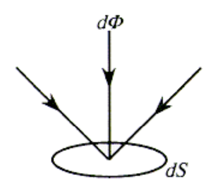
Radiant intensity I_e

Radiant energy radiated from a point source per solid angle in a radial direction per unit time



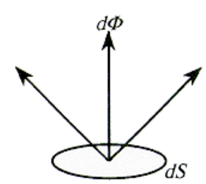
Irradiance E_e

Radiant energy incident upon a unit area per unit time



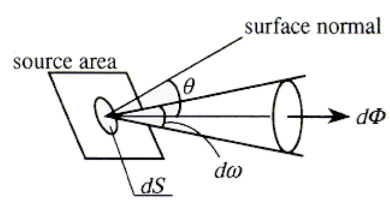
Radiant emittance M_e

Radiant energy radiated from a unit area per unit time

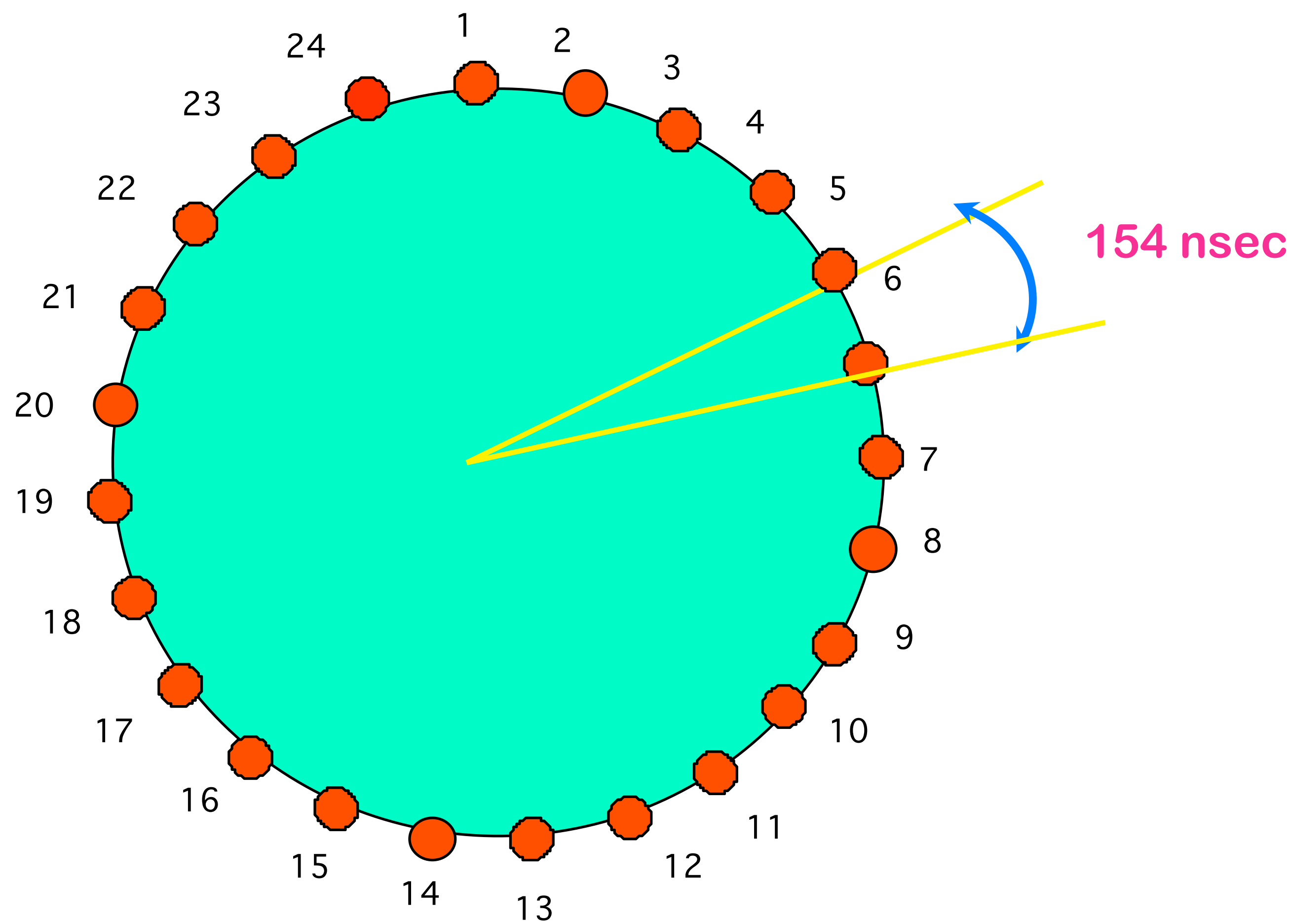


Radiance L_e

Radiant energy radiated from a unit projected area per unit solid angle in a radial direction per unit time

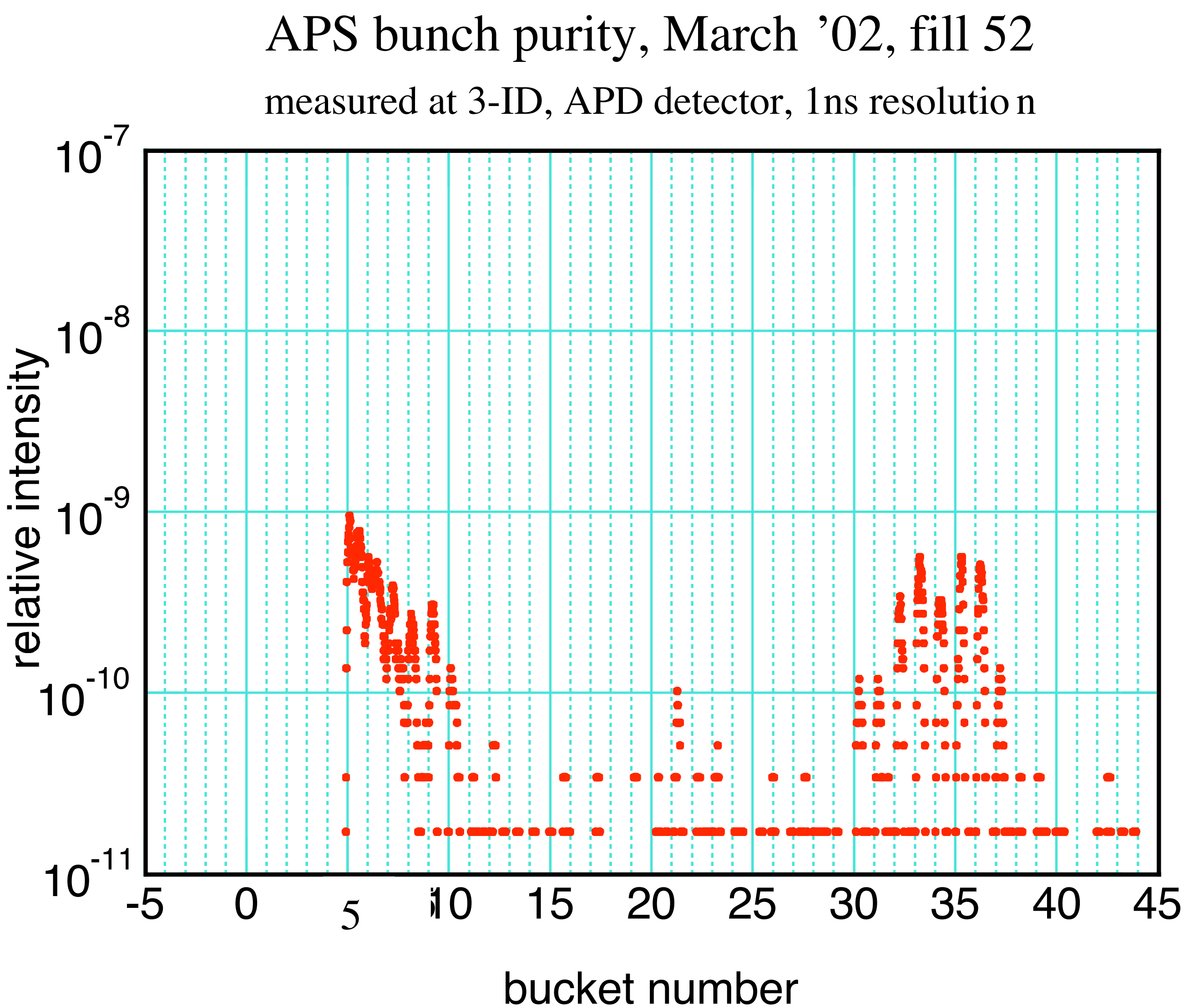


Standard Time structure @ APS



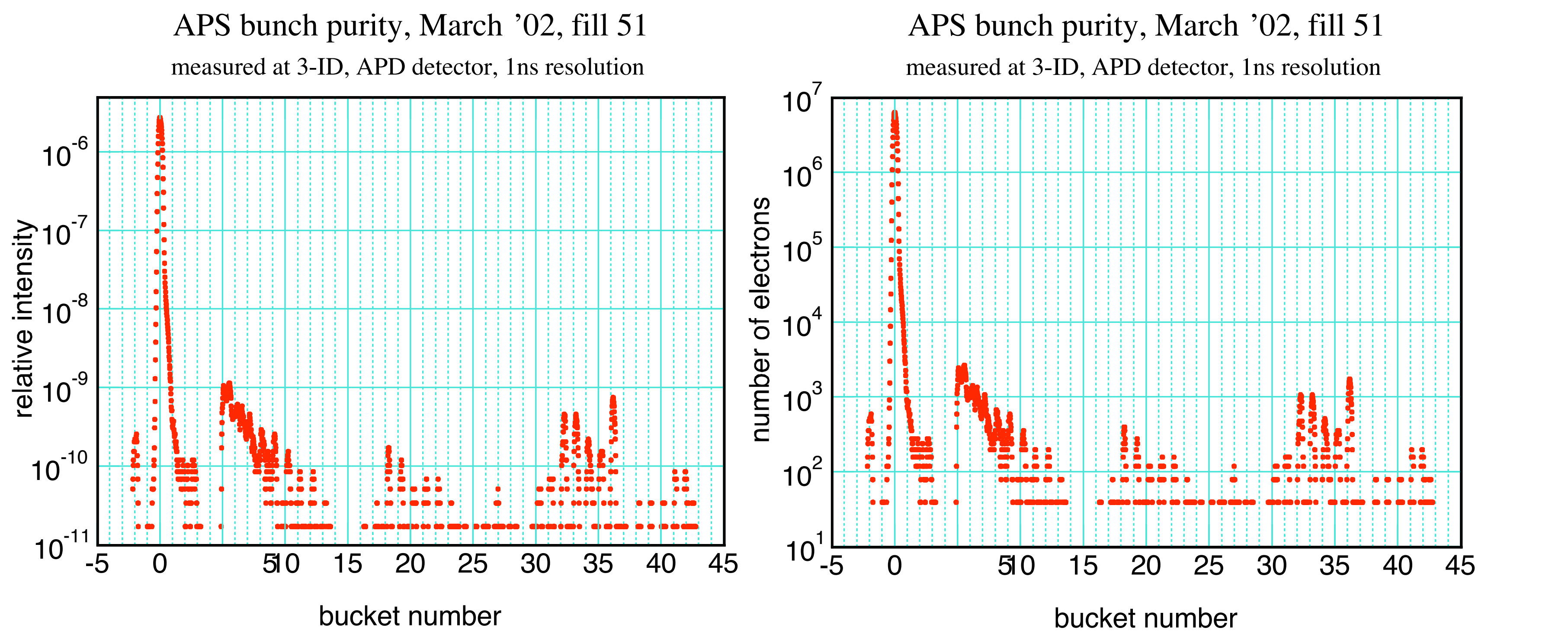
1 revolution=3.68 μsec =>1296 buckets

Bunch Purity



W. Sturhahn, March 03, 2002

How many electrons can we actually see ?



1 Ampere = 1 Coulomb/sec = $6.24 \cdot 10^{18}$ electron/sec

1 bunch at 5 mA has $1.15 \cdot 10^{11}$ electrons

Photon flux = 10^{10} Hz/1meV, i.e $5 \cdot 10^{8}$ Hz/bunch/meV

APD noise ~ 0.01 Hz => 1 part in 10^{10} purity ideal

Metrology: The science that deals with measurement.

High Resolution: $R > 10^6$ (arbitrary)

Normal Incidence: Bragg diffraction at 90°

Hard X-Rays: $E > 2$ keV, $\lambda < 6$ Å (arbitrary)

Thermal expansion coefficient: $\alpha = \frac{1}{a}\frac{\partial a}{\partial T}$

Isotopic dependence of lattice constant : $a_0 = a_\infty + CM^{-1/2}$

Avogadro's constant

One needs to have an accurate knowledge of

1. Volume per silicon atom
2. Macroscopic density of Si
3. The isotopic composition (Si 28,29, and 30)

Point defects, impurities, and surface defects are all sources of uncertainty

Advantages of synchrotron radiation !

- Variable wavelength
  - –Index-of-refraction correction exceeds absorption length below 10 keV

$$\delta(\lambda) = \frac{r_e \lambda^2}{2\pi V} \sum_a N_a \left[Z_a + f_a'(\lambda) \right]$$

  - –Extinction length and absorption length can be adjusted with back-scattering and temperature
- Collimation
  - –Extreme collimation down to 1 μrad is critical
- Mössbauer wavelength standards accessible

  6.4 to 100 keV

What were our "guns" ?

Monochromators (6-100 keV)

Nano-positioners & precision engineering

sub-Å positioners and encoders

Normal Incidence Diffraction and 3-ID-C:

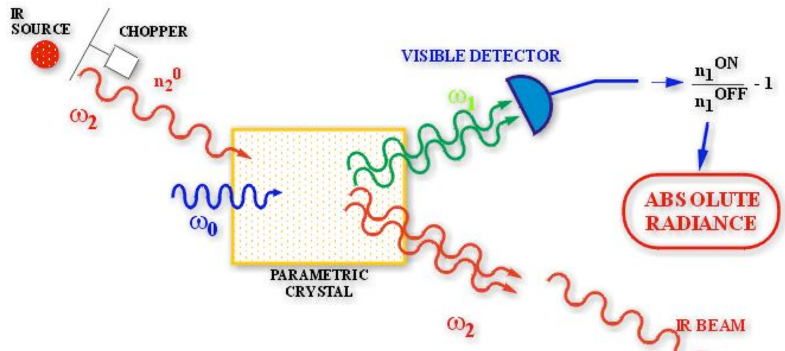
the know-how and the beamline

Time discrimination (sub-nanosecond)

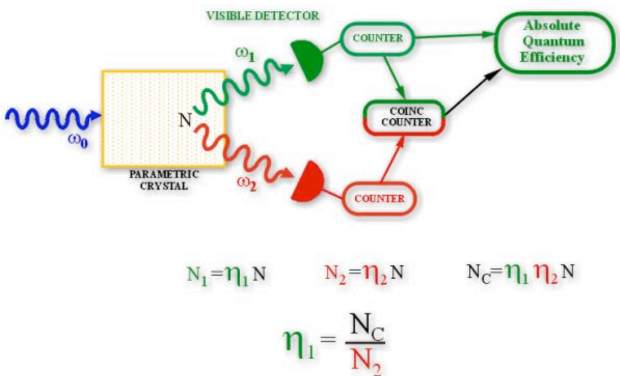
Experience in ultra-precision measurements

vibration isolation, stiffness, reproducibility

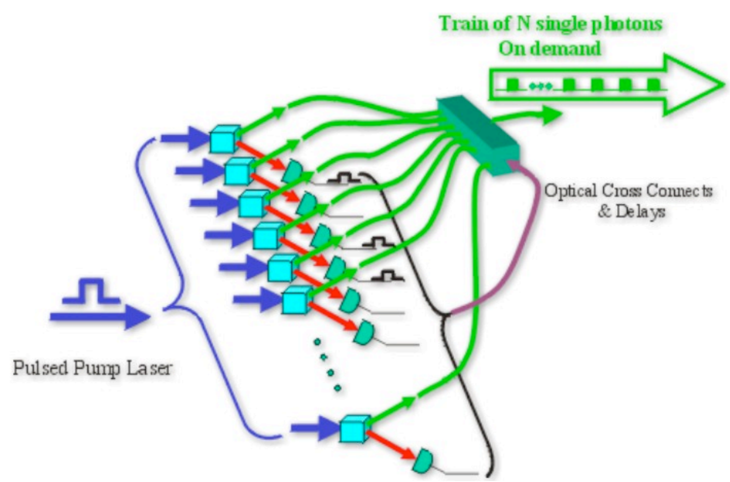
Correlated Photon Radiometry at NIST



Absolute radiance measurements of high temperature IR sources

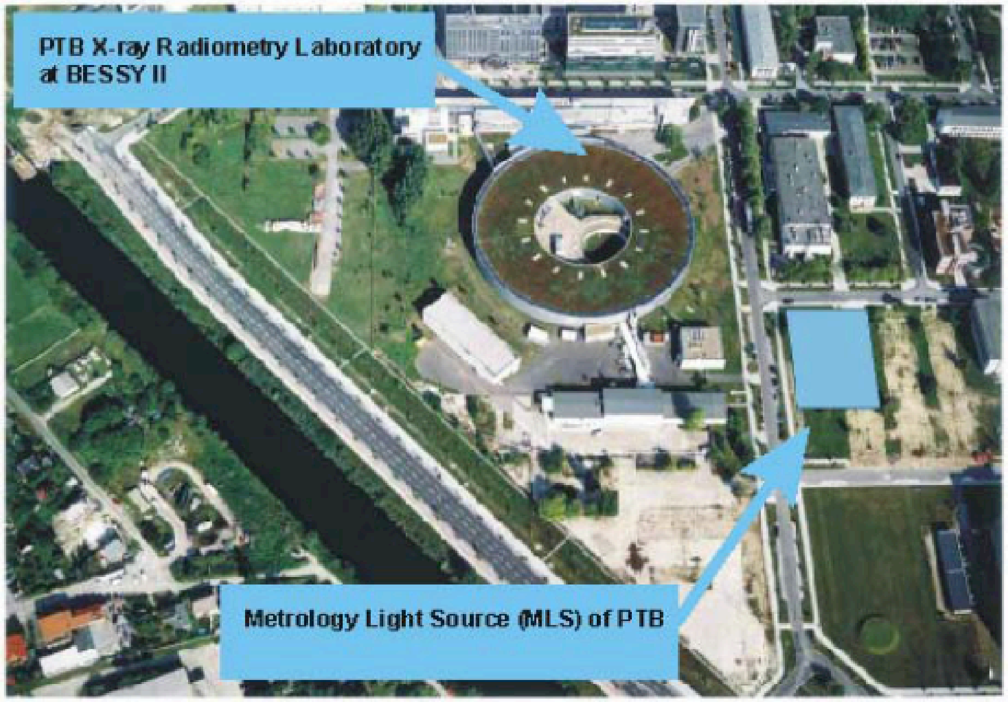


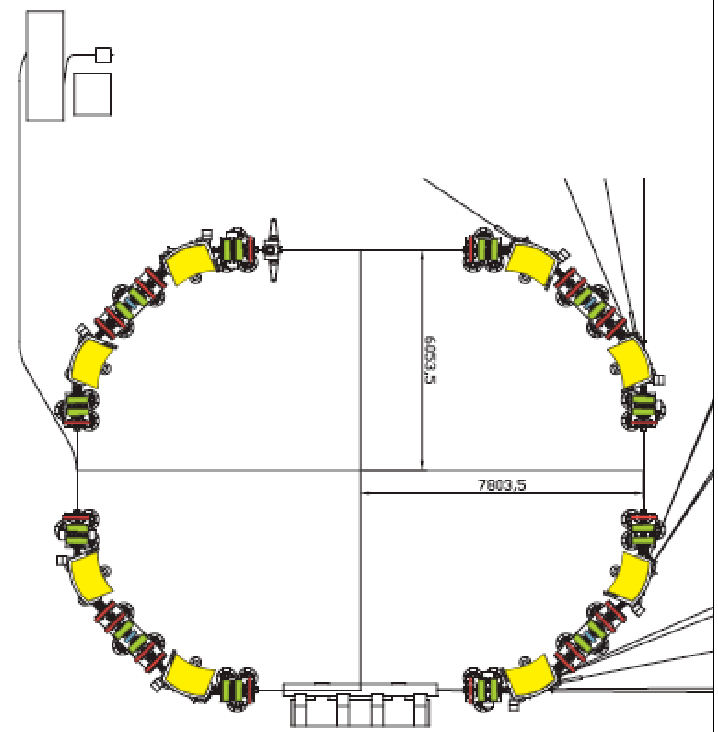
Determining the absolute response of photon counting detectors

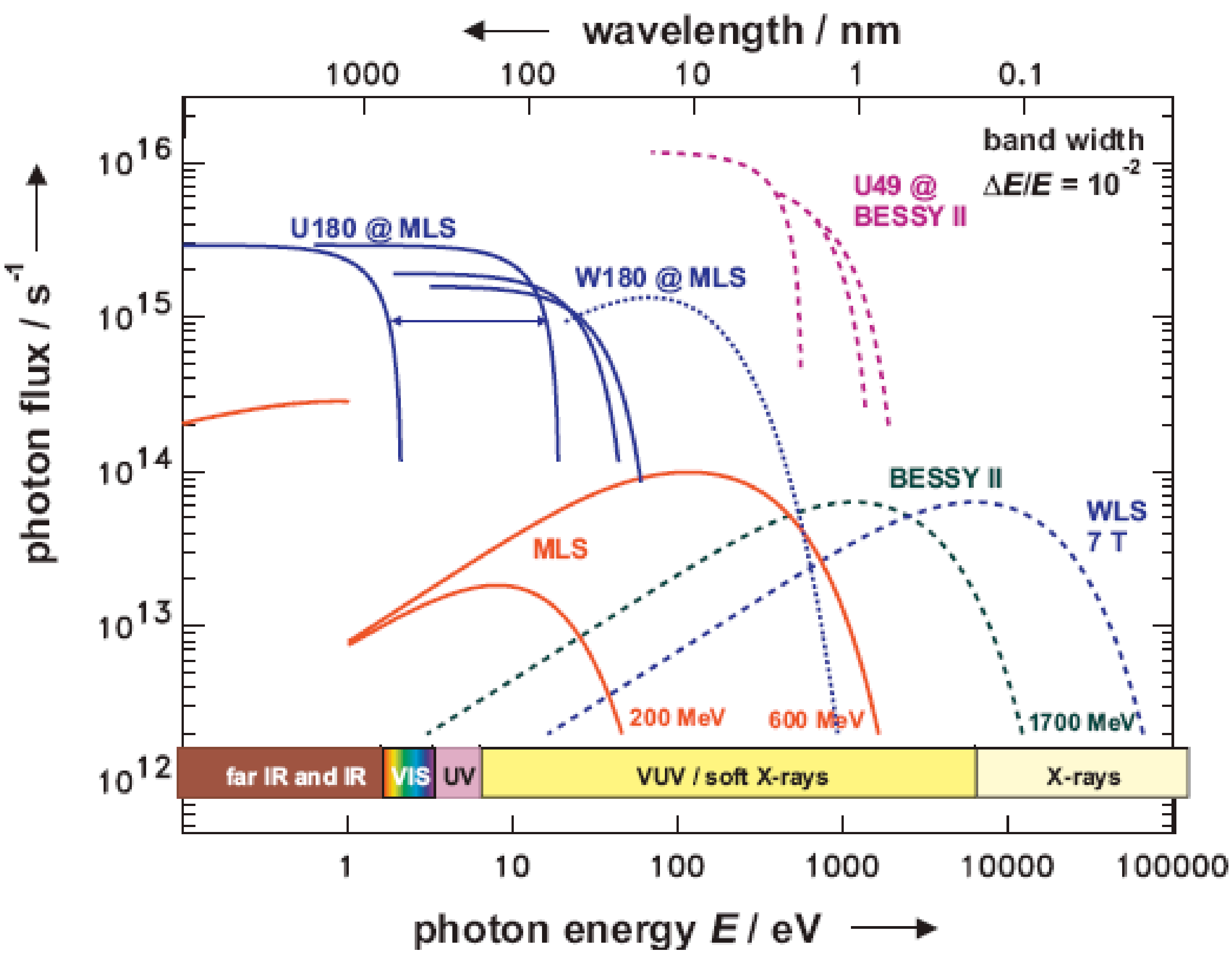


Single-photon on-demand source

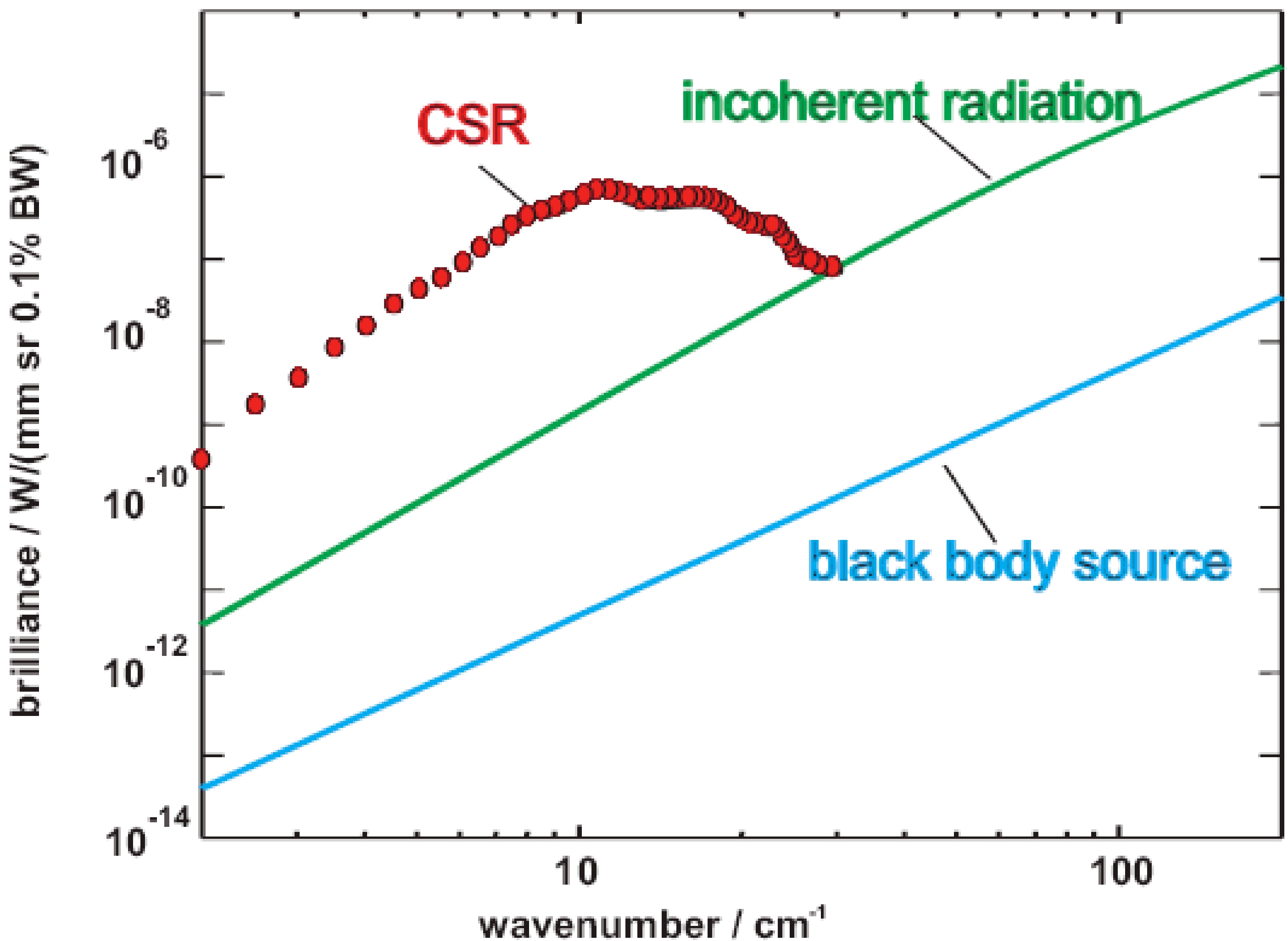
http://physics.nist.gov/Divisions/Div844/facilities/cprad/cprad.html


PTB X-ray Radiometry Laboratory at BESSY II
Metrology Light Source (MLS) of PTB


6053,5
7803,5



wavelength / nm
1000
100
10
1
0.1
band width
$\Delta E/E = 10^{-2}$
U49 @ BESSY II
U180 @ MLS
W180 @ MLS
BESSY II
WLS 7 T
MLS
200 MeV
600 MeV
1700 MeV
far IR and IR
VIS
UV
VUV / soft X-rays
X-rays
photon flux / s^{-1}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
1
10
100
1000
10000
100000
photon energy E / eV


CSR
incoherent radiation
black body source
brilliance / W/(mm sr 0.1% BW)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10
100
wavenumber / cm^{-1}